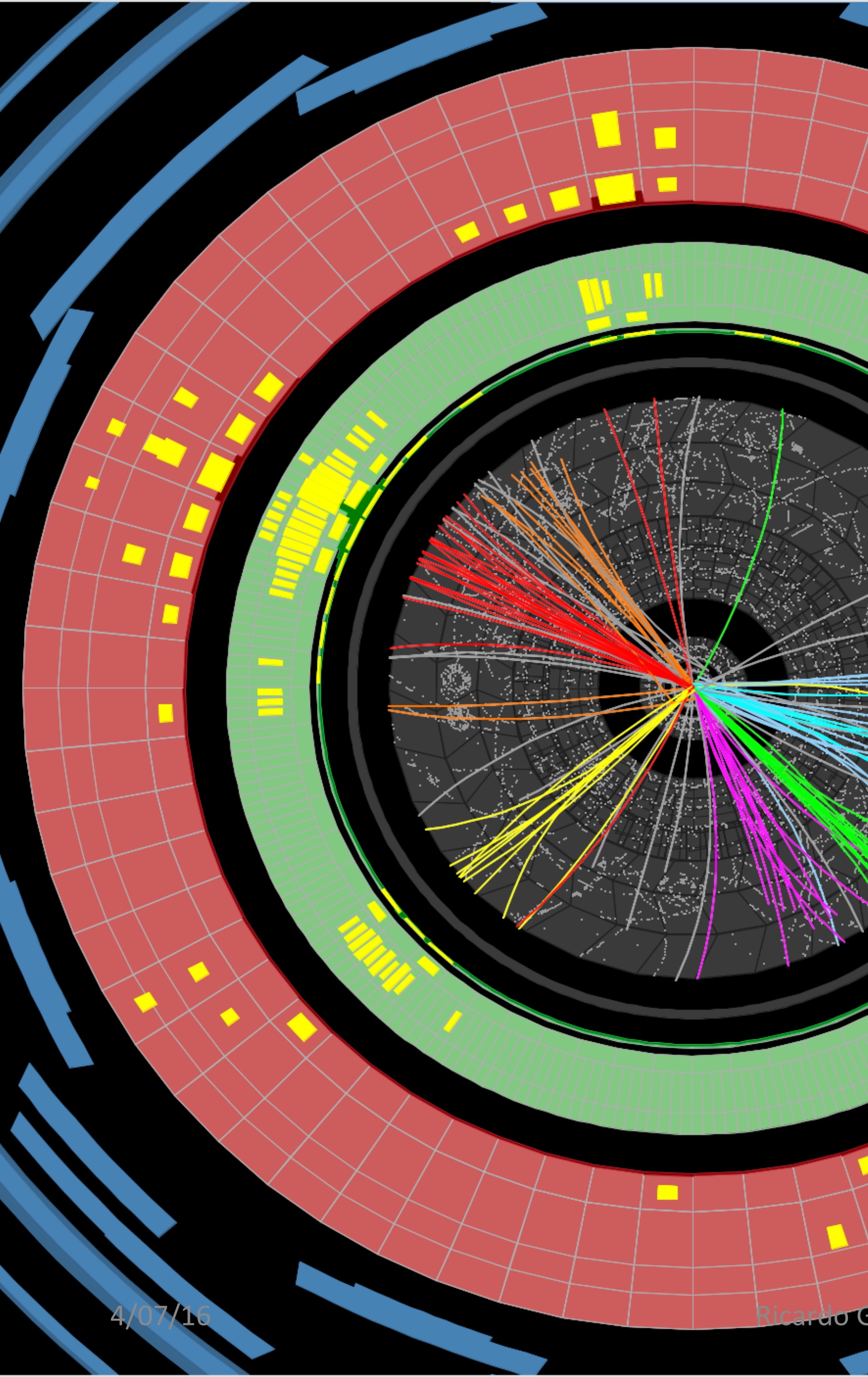
Search for the 125 GeV Higgs boson in ttH production with ATLAS

Ricardo Gonçalo (LIP), on behalf of the ATLAS Collaboration



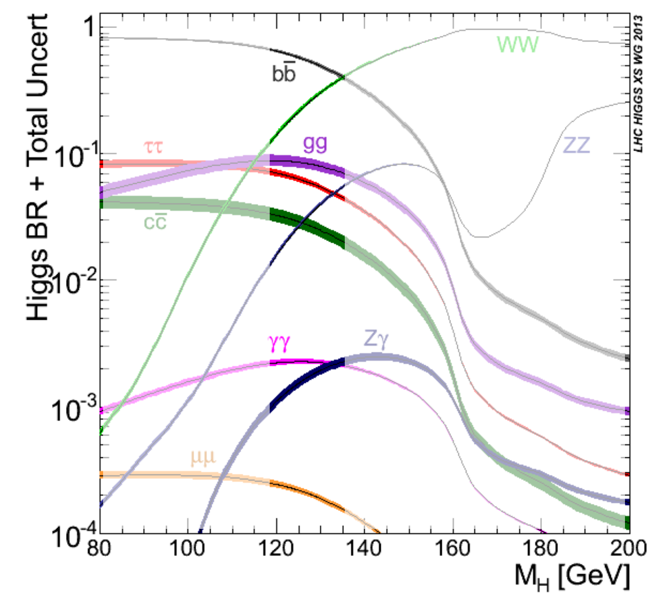
Outline

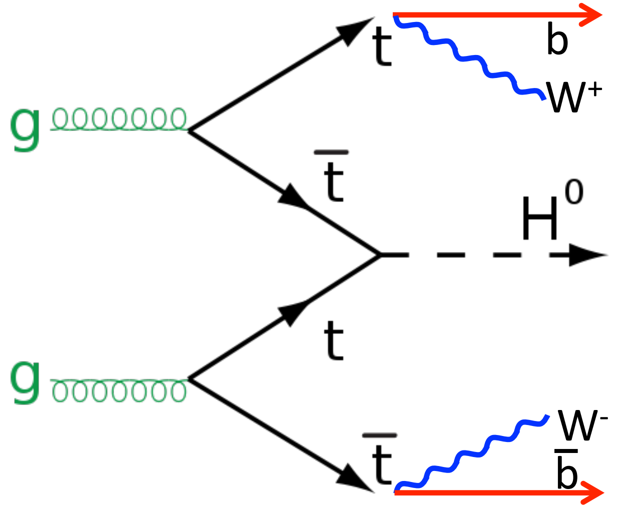
No LHC Run 2 results yet. But soon!

- Introduction
- Final LHC Run 1 results
  - H → γγ
  - Multilepton final states
  - H → bb:
    - di-leptonic
    - lepton+jets
    - all-hadronic
- Looking forward

Introduction

- Why should we care about ttH?
  - Measure largest SM Yukawa coupling ($y_{top} \approx 1$)
  - Direct measurement of y_{top} – unlike gluon-fusion!
  - y_{top} connected to the scale of new physics (arXiv: 1411.1923 [hep-ph])
  - Complementary channel to extract Higgs CP (arXiv:1501.03157 [hep-ph], arXiv:hep-ph/9602226, arXiv:1312.5736 [hep-ph])
- But :
  - Small cross section:
    - 0.506pb @ 13 TeV, 0.136pb @ 8 TeV
    - ≈ 0.7% – 1.1% of gluon-fusion Higgs production
  - Complicated final states: many possible Higgs and top decay combinations
  - Draws on all detector capabilities
  - Problematic combinatorial issues in event reconstruction for most channels
- So:
  - Favour high branching ratio decays: bb, WW, ττ
  - Or H->γγ (low BR but no comb. issues there)
  - Make analyses orthogonal to ease combination





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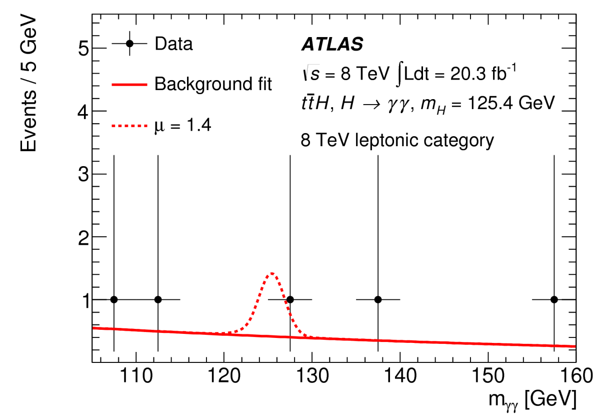
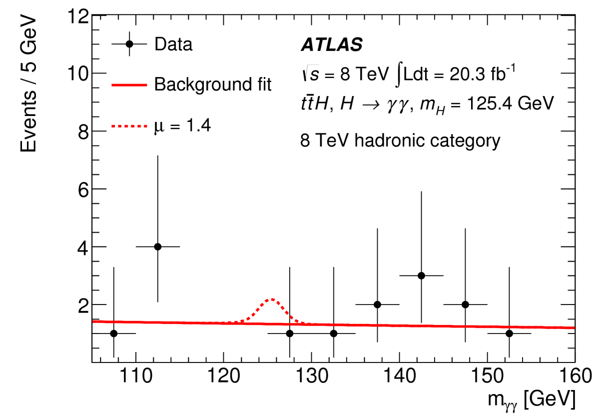
ttH, H→γγ analysis

- Analysis targets ttH and tH production (tHqb, tHW)
- Data: 4.5 fb^{-1} at √s = 7 TeV and 20 fb^{-1} at √s = 8 TeV
- Very small BR(H → γγ) = 0.0023
  - Event yields: ≈0.2 at 7 TeV; ≈1 at 8 TeV
  - But good di-photon mass resolution and small backgrounds
- Analysis driven by ttH, but cuts loose enough to accommodate tH
  - Efficiency ≈15% for ttH, ≈6% to 12% for tH
- Selection:
- 2 photons with 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
  - Diphoton vertex reconstructed from longitudinal shower profile (un-converted) or tracks (converted photons)
  - Leading (subleading) photon: $E_T > 0.35 \times m_{\gamma\gamma}$ ($0.25 \times m_{\gamma\gamma}$)
- 2 event categories:
  - Leptonic: ≥ 1 e/μ + ≥ 1 b-tagged jet + E_T^{miss} > 20 GeV; $m_{\ell e} \neq m_Z$
  - Hadronic: no e or μ; high jet and b-tag multiplicity





Category	N_H	% of signal: ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH	N_B
7 TeV leptonic selection	0.10	0.6	0.1	14.9	4.0	72.6	5.3	2.5	$0.5^{+0.5}_{-0.3}$
7 TeV hadronic selection	0.07	10.5	1.3	1.3	1.4	80.9	2.6	1.9	$0.5^{+0.5}_{-0.3}$
8 TeV leptonic selection	0.58	1.0	0.2	8.1	2.3	80.3	5.6	2.6	$0.9^{+0.6}_{-0.4}$
8 TeV hadronic selection	0.49	7.3	1.0	0.7	1.3	84.2	3.4	2.1	$2.7^{+0.9}_{-0.7}$

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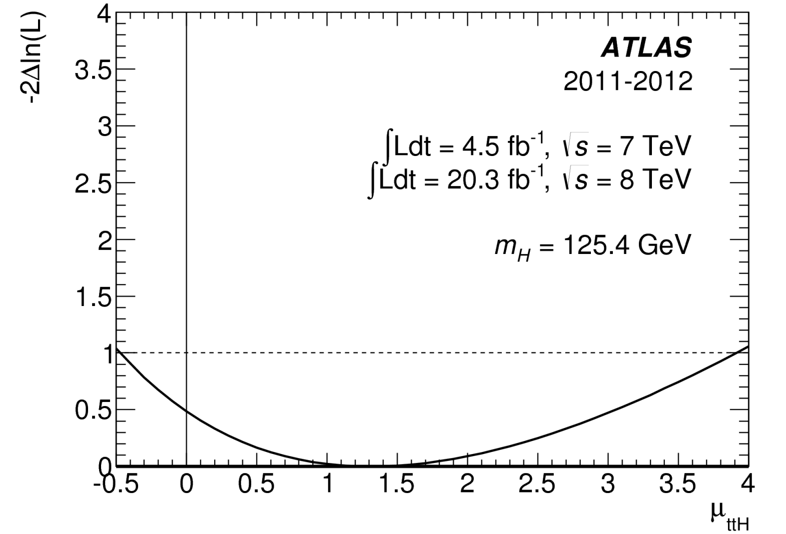
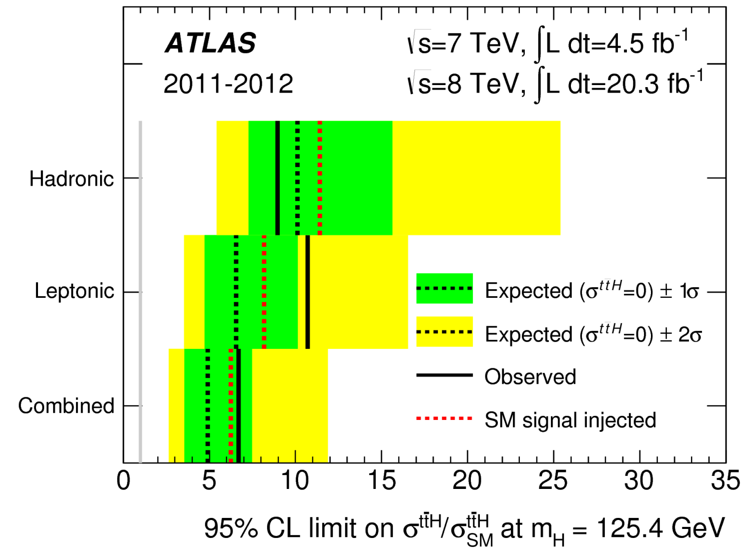
Analysis & Results

- Discriminant parameter: $m_{\gamma\gamma}$
  - Search excess around 125.4 GeV using S + B likelihood fit
  - Signal modelling: Crystal Ball + Gaussian (from simulation)
  - Continuum background: exponential fit to sideband
  - Fit function validated in loose photon-ID control regions dominated by jets
- Signal strength ($\mu_{ttH} = \sigma_{obs.}/\sigma_{SM}$) best fit:
  - Overall ($H \rightarrow \gamma\gamma$): $1.4^{+2.1}_{-1.4}(\text{stat.})^{+0.6}_{-0.3}(\text{syst.})$
  - ttH only: $1.3^{+2.5}_{-1.7}(\text{stat.})^{+0.8}_{-0.4}(\text{syst.})$
- Combined limits on signal strength

  $\mu < 6.7$ (4.9 expected)
- Interpreting the data as 95% CL interval of a constant κ_t multiplying the top Yukawa coupling ($y_t = \kappa_t\, y_t^{SM}$):
  - Observed: $-1.3 < \kappa_t < 8.0$
  - Expected: $-1.2 < \kappa_t < 7.8$

$\mu_{ttH} = \sigma_{obs.}/\sigma_{SM}$





ttH multilepton analysis

- Targets mostly H→WW and H→ττ decays (medium BR); also H→ZZ
- 5 orthogonal event categories: $2\ell 0\tau_{had}$, 3ℓ, $2\ell 1\tau_{had}$, 4ℓ, $1\ell 2\tau_{had}$
- Analyzed 20 fb^{-1} of data at $\sqrt{s}$ = 8 TeV
- Low-stats counting analysis:
  - Total ≈10 signal events expected (0.4% eff.) but also low backgrounds
- Selection designed to suppress tt background

  - $2\ell 0\tau_{had}$: 2 same-sign $e^{\pm}/\mu^{\pm}$; no τ_{had}
  - 3ℓ : 3 $e^{\pm}$ or $\mu^{\pm}$ (total charge ±1)
  - $2\ell 1\tau_{had}$: 2 same-sign e/μ and 1 τ_{had}
  - 4ℓ : 4 $e^{\pm}$ or $\mu^{\pm}$ (zero total charge)
  - $1\ell 2\tau_{had}$: 1 $e^{\pm}$ or $\mu^{\pm}$ and 2 τ_{had}
  - Variable number of jets depending on category => suppress specific backgrounds

	Higgs boson decay mode			
Category	WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{\rm had}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{\rm had}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{\rm had}$	4%	93%	0%	3%

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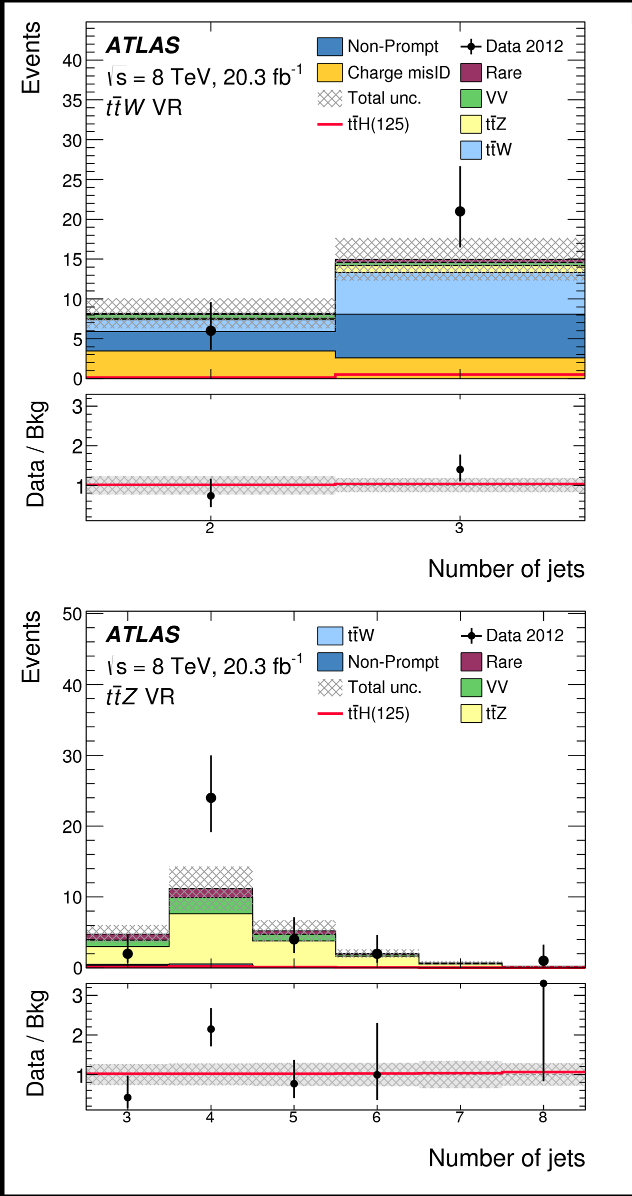
Backgrounds and uncertainties

- Signal final states: WWWWbb, ττWWbb, ZZWWbb
- Backgrounds:
- ttW and ttZ (WWWbb, ZWWbb):
  - Estimated from simulation and verified in validation regions
  - ttW in $2\ell0\tau_{had}$: same as $2\ell0\tau_{had}$ signal but only ≤ 3 jets
  - ttZ in 3ℓ, $2\ell1\tau_{had}$, 4ℓ, $1\ell2\tau_{had}$: validate in $Z\to\ell\ell$ region
  - Uncertainties up to ≈30% in signal regions
- Dibosons, especially WZ + jets:
  - Estimated from simulation and verified in validation regions (e.g. Z + b-jets for 3ℓ)
  - Main uncertainty from WZ + b x-section (100% assigned)
  - Uncertainties up to ≈50% in signal regions
- Electron charge mis-identification:
  - Mainly from $e^{\pm} \to e^{\pm}\gamma \to e^{\pm}e^{+}e^{-}$ and grows with η (material)
  - Estimated from $Z\to\ell\ell$ data and extrapolated using simulation
  - Negligible for muons and track curvature (instrumental)
  - Uncertainties up to ≈40% in signal regions
- Non-prompt leptons:
  - Can e.g. promote tt events to $2\ell0\tau_{had}$ or 3ℓ categories
  - Estimated from data control regions – inverting lepton cuts
  - Uncertainties of ≈20 - 50% in signal regions
- Fake τ_{had} identification (important in $1\ell2\tau_{had}$)
  - 3 data control regions with loose τ_{had} identification



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Signal regions

Most sensitive: $2\ell 0\tau_{had}$, 3ℓ – dominated by H→WW

Followed by $2\ell 1\tau_{had}$ – dominated by H→ττ and H→WW

$2\ell 0\tau_{had}$

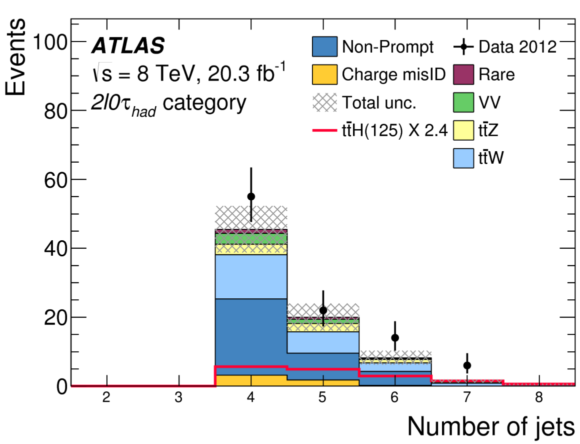
3ℓ

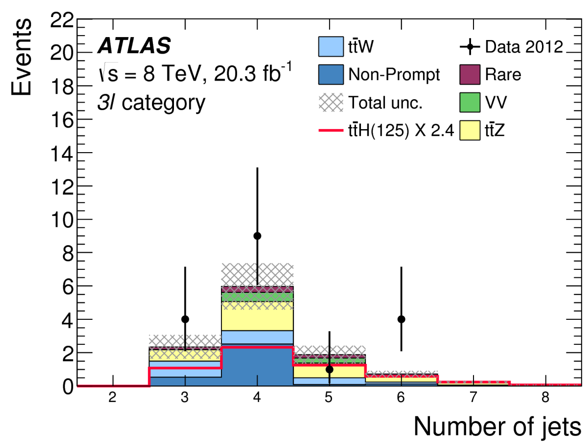
$2\ell 1\tau_{had}$

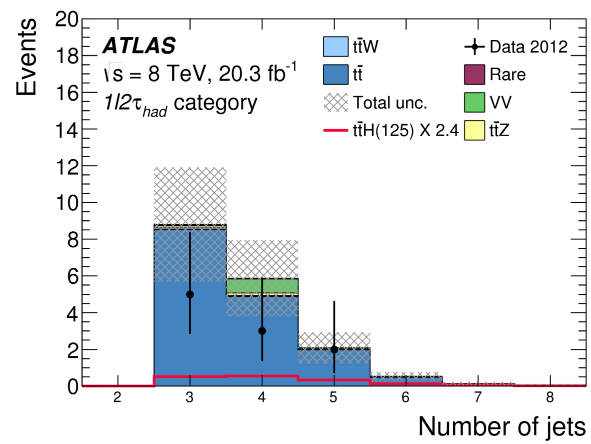
$1\ell 2\tau_{had}$

4ℓ

Category	q mis-id	Non-prompt	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Expected bkg.	$t\bar{t}H$ $(\mu = 1)$	Observed
$ee + \geq 5j$	1.1 ± 0.5	2.3 ± 1.2	1.4 ± 0.4	0.98 ± 0.26	0.47 ± 0.29	6.5 ± 1.8	0.73 ± 0.14	10
$e\mu + \geq 5j$	0.85 ± 0.35	6.7 ± 2.4	4.8 ± 1.2	2.1 ± 0.5	0.38 ± 0.30	15 ± 3	2.13 ± 0.41	22
$\mu\mu + \geq 5j$	–	2.9 ± 1.4	3.8 ± 0.9	0.95 ± 0.25	0.69 ± 0.39	8.6 ± 2.2	1.41 ± 0.28	11
$ee + 4j$	1.8 ± 0.7	3.4 ± 1.7	2.0 ± 0.4	0.75 ± 0.20	0.74 ± 0.42	9.1 ± 2.1	0.44 ± 0.06	9
$e\mu + 4j$	1.4 ± 0.6	12 ± 4	6.2 ± 1.0	1.5 ± 0.3	1.9 ± 1.0	24 ± 5	1.16 ± 0.14	26
$\mu\mu + 4j$	–	6.3 ± 2.6	4.7 ± 0.9	0.80 ± 0.22	0.53 ± 0.30	12.7 ± 2.9	0.74 ± 0.10	20
3ℓ	–	3.2 ± 0.7	2.3 ± 0.7	3.9 ± 0.8	0.86 ± 0.55	11.4 ± 2.3	2.34 ± 0.35	18
$2\ell 1\tau_{\mathrm{had}}$	–	$0.4\,^{+0.6}_{-0.4}$	0.38 ± 0.12	0.37 ± 0.08	0.12 ± 0.11	1.4 ± 0.6	0.47 ± 0.08	1
$1\ell 2\tau_{\mathrm{had}}$	–	15 ± 5	0.17 ± 0.06	0.37 ± 0.09	0.41 ± 0.42	16 ± 5	0.68 ± 0.13	10
4ℓ Z-enr.	–	$\lesssim 10^{-3}$	$\lesssim 3 \times 10^{-3}$	0.43 ± 0.12	0.05 ± 0.02	0.55 ± 0.15	0.17 ± 0.02	1
4ℓ Z-dep.	–	$\lesssim 10^{-4}$	$\lesssim 10^{-3}$	0.002 ± 0.002	$\lesssim 2 \times 10^{-5}$	0.007 ± 0.005	0.025 ± 0.003	0







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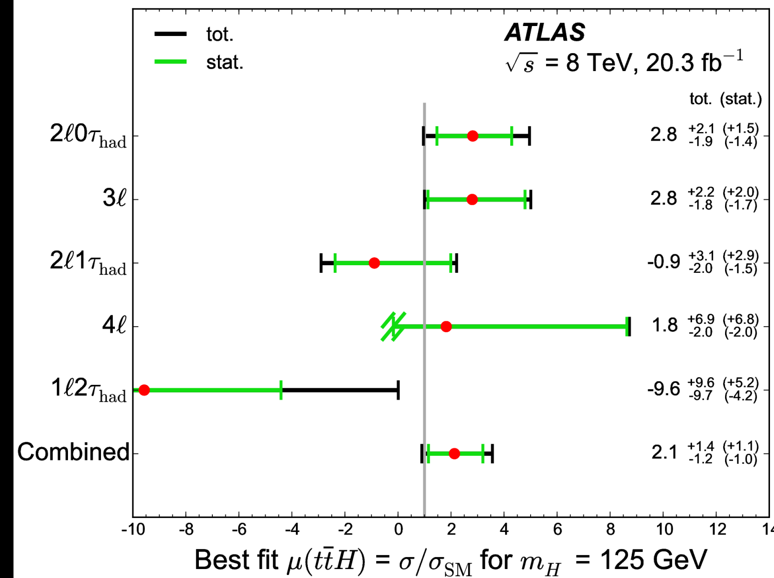
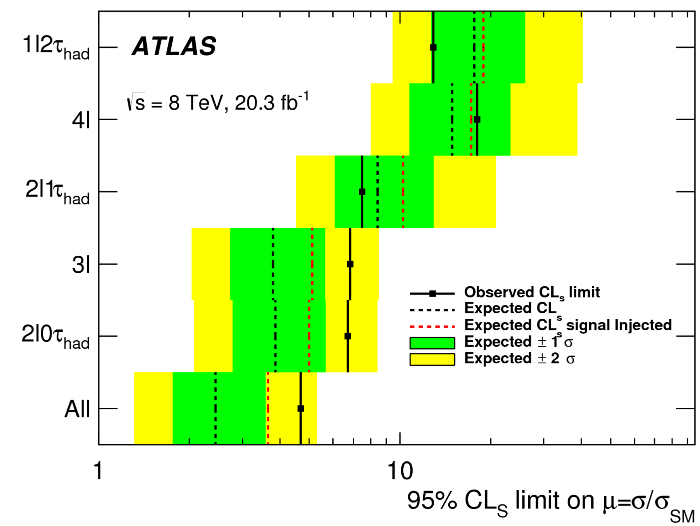
Results

- Signal strength $\mu_{ttH} = \sigma_{obs.}/\sigma_{SM}$ from maximum-likelihood fit to yields in all categories
  - Systematic uncertainties are nuisance parameters in fit
  - μ_{ttH}=1 assumes SM x-sections and BR, and m_H = 125 GeV
  - Fit constrains statistically-limited non-prompt leptons
- Small excess in combined signal strength from $2\ell 0\tau_{had}$, 3ℓ categories – compatible with SM
- Combined 95% CL exclusion limit on is $\mu_{ttH} < 4.7$ ($\mu_{ttH} < 2.4$ expected)
- Single top tH production was set to SM value
  - Setting it to zero gives a variation Δμ of 0.04

$\mu_{ttH} = \sigma_{obs.}/\sigma_{SM}$



Source	Combination of all categories	$\Delta\mu$	
$2\ell 0\tau_{had}$ non-prompt muon transfer factor		+0.38	−0.35
$t\bar{t}W$ acceptance		+0.26	−0.21
$t\bar{t}H$ inclusive cross section		+0.28	−0.15
Jet energy scale		+0.24	−0.18
$2\ell 0\tau_{had}$ non-prompt electron transfer factor		+0.26	−0.16
$t\bar{t}H$ acceptance		+0.22	−0.15
$t\bar{t}Z$ inclusive cross section		+0.19	−0.17
$t\bar{t}W$ inclusive cross section		+0.18	−0.15
Muon isolation efficiency		+0.19	−0.14
Luminosity		+0.18	−0.14



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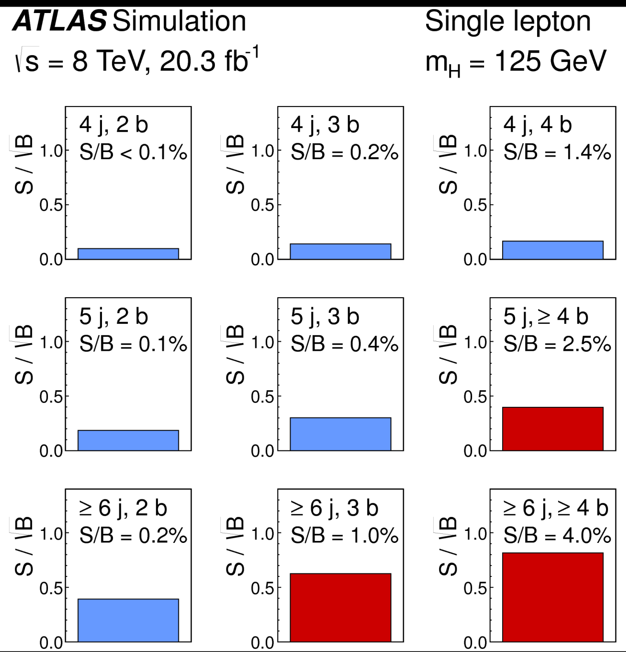
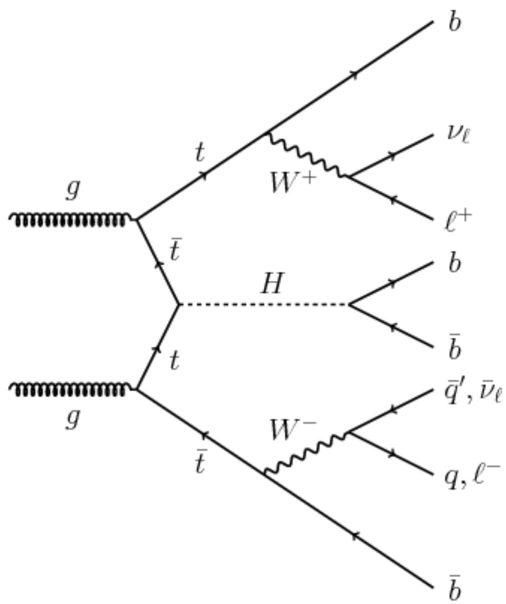
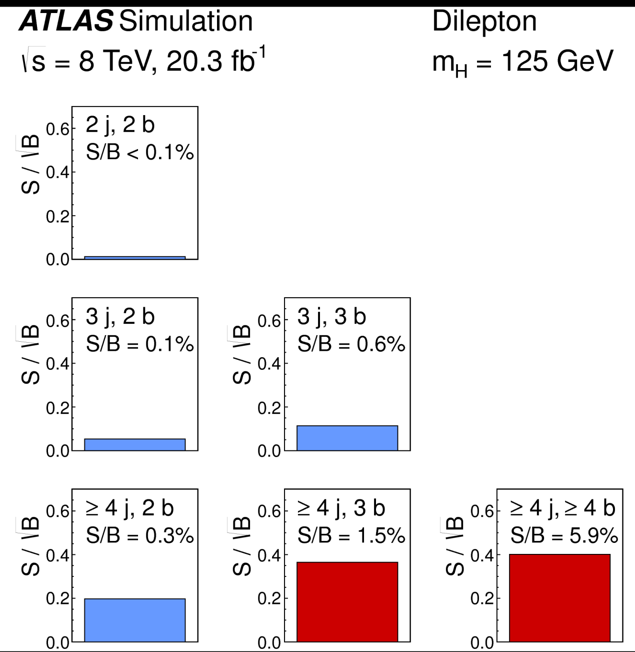
ttH(H→bb) with ≥1 lepton

- Analyzed 20.3 fb^{-1} of data at √s = 8 TeV
- Benefit from high BR(H→bb) = 58%
- Avoid full event reconstruction – plagued by combinatorial errors
- Main difficulty: accurate modeling of large or poorly-known backgrounds
- Two channels: "single-lepton" and "dilepton" (lepton = $e^{\pm}$ or $\mu^{\pm}$)
  - Single-lepton channel: 1 good $e^{\pm}$ or $\mu^{\pm}$ + ≥ 4 jets, ≥ 2 are b-tagged
  - Dilepton channel: 2 $e^{\pm}$ or $\mu^{\pm}$ (opposite charge) + ≥ 4 jets, ≥ 2 are b-tagged
  - Several categories according to nr. of jets and *b*-tags – to enhance sensitivity and constrain backgrounds!



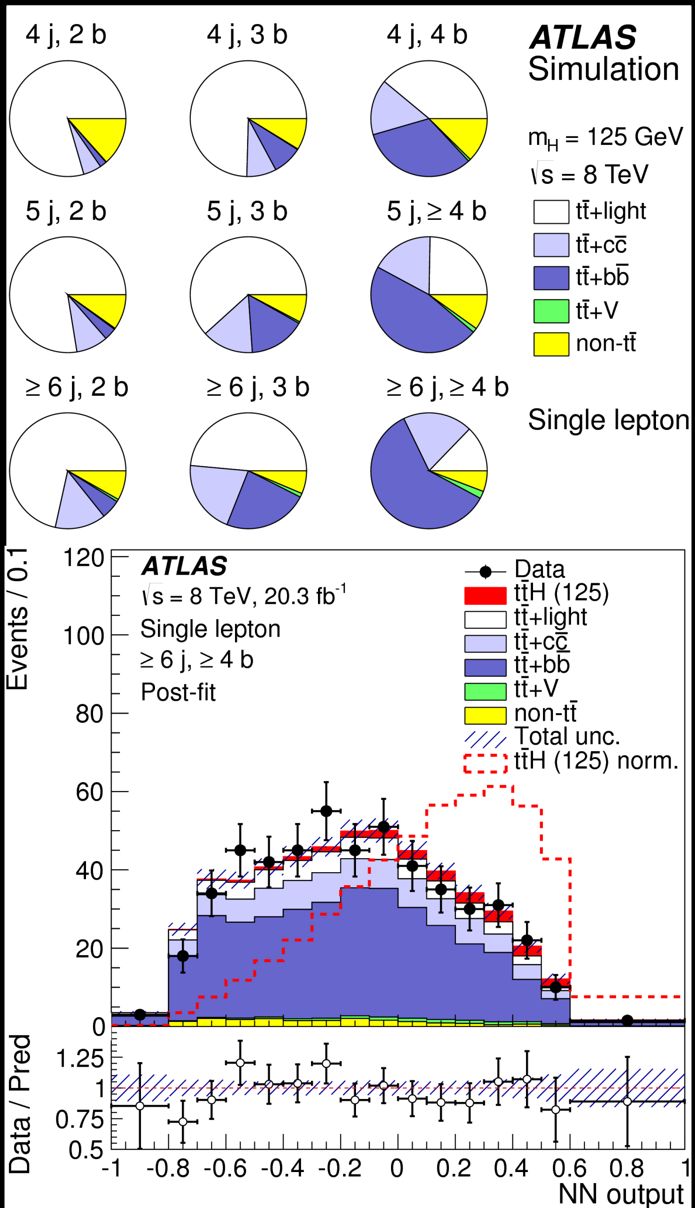




Analysis

- Use H_T^{had} in low S/B regions to constrain various backgrounds in simultaneous fit
- Neural Network (NN) in signal-rich regions
  - In single-lepton channel: two Matrix Element Method variables used as input to NN – most discriminating NN input!
- Much attention paid to modeling of important backgrounds: tt + jets, ttW/Z, W/Z + jets
  - tt + bb is irreducible background in both channels
- In single-lepton channel: NN to separate tt + light jets from tt + Heavy Flavours in 5j,3b category
  - Target tt+c (from W→cs) through 3rd b-tagged jet

	2 b-tags	3 b-tags	4 b-tags
4 jets	H_T^{had}	H_T^{had}	H_T^{had}
5 jets	H_T^{had}	NN (tt+j vs H.F.)	NN
≥6 jets	H_T^{had}	NN	NN



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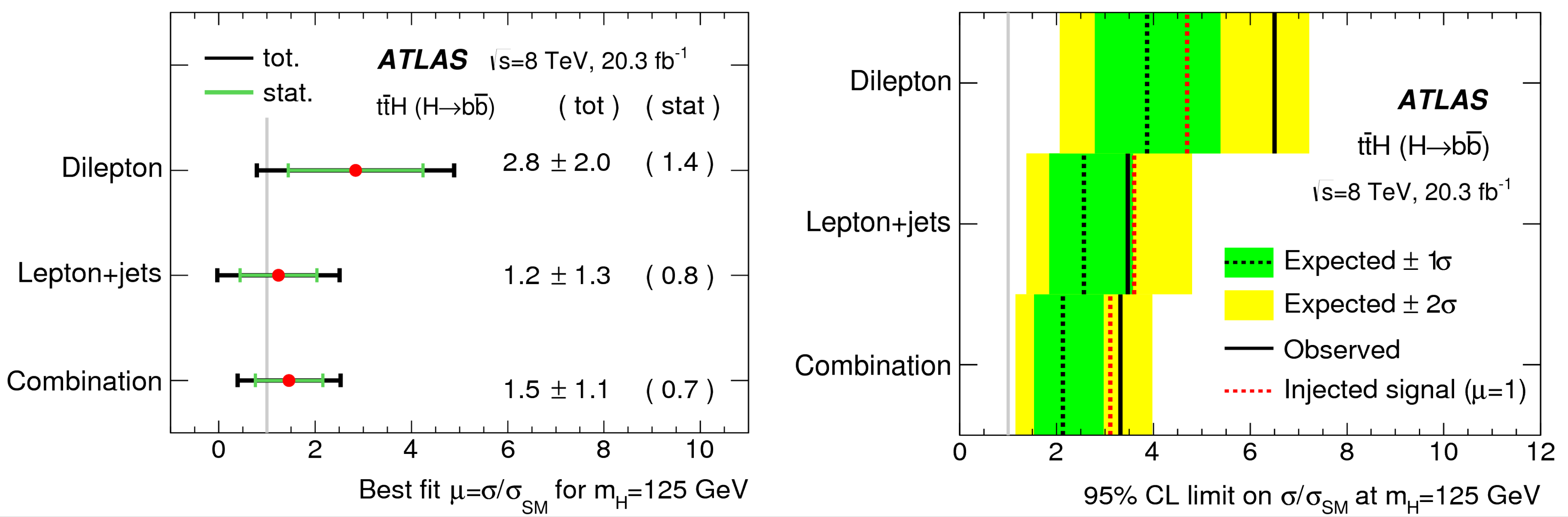
Results

- Signal strength from combined H→bb single-lepton and dilepton channels: $\mu_{ttH} = \sigma_{obs.}/\sigma_{SM} = 1.5 \pm 1.1$
- Exclusion limits at 95% CL: μ < 3.4 (2.2 expected)
- Most important uncertainties:
  - tt + Heavy Flavour modeling
  - Jet energy scale
  - ttV cross section



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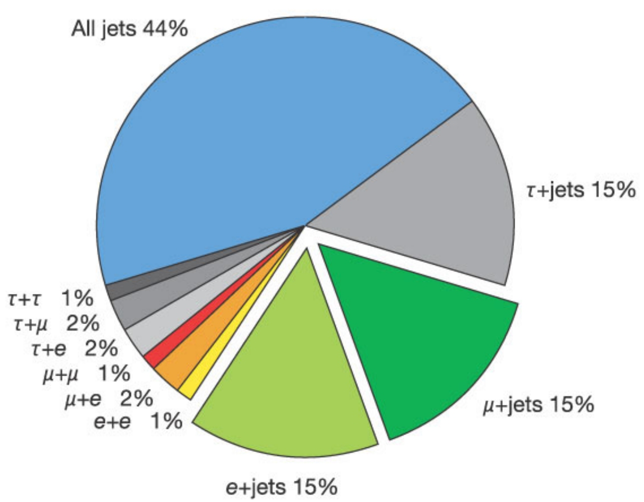
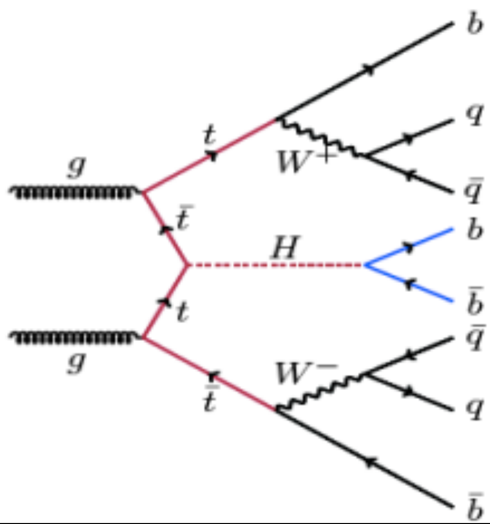
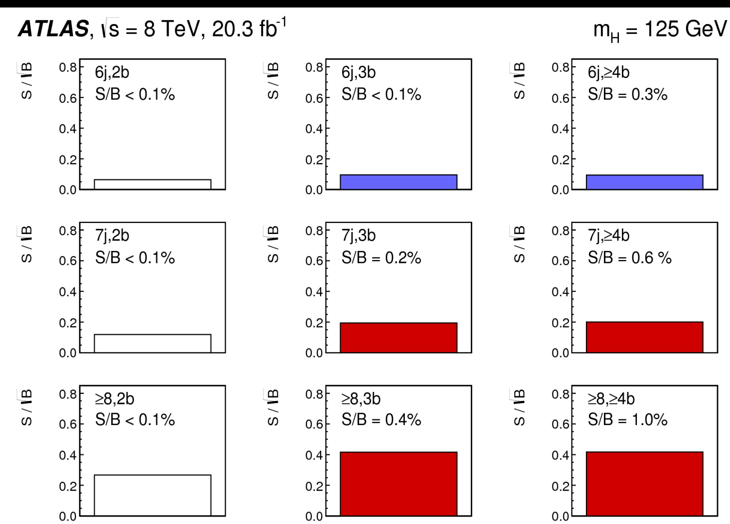
ttH(H→bb) all-hadronic

- Analyzed 20.3 fb^{-1} of data at √s = 8 TeV
- Benefit from high BR(H→bb) = 58% AND high tt BR to jets = 44%
- Main difficulty: large multijet background
- Selection:
  – 5-jet trigger with p_T > 55 GeV, |η| < 2.5
  – No good electrons or muons with p_T > 25 GeV – orthogonality with other H→bb analyses
  – ≥ 6 jets ; ≥ 2 jets b-tagged
  – 5 leading jets with p_T > 55 GeV, |η| < 2.5; other jets p_T > 55 GeV, |η| < 2.5







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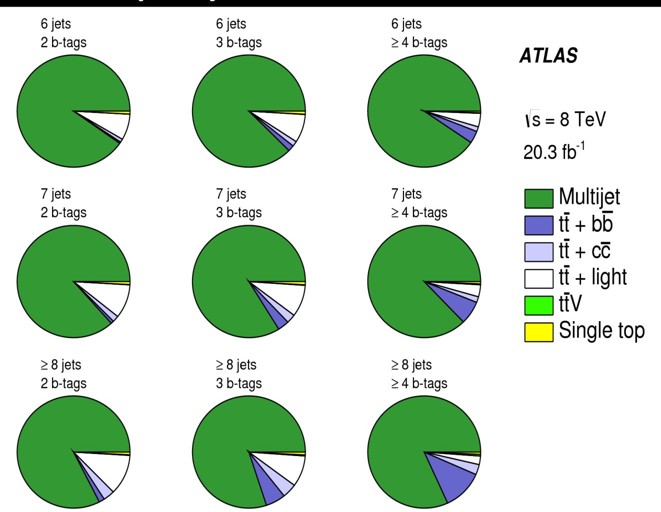
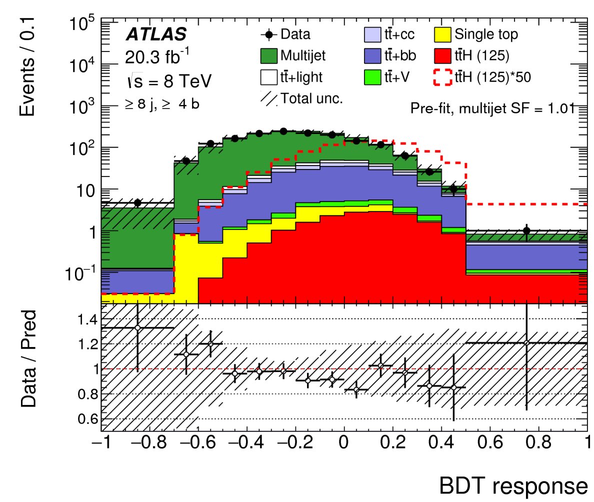
Analysis

- Categories according to nr. of jets and *b*-tags
  - 2 b-tag events used to extract multijet backgr.
- Backgrounds:
  - Multijet production is dominant background;
  - Followed by tt + jets
  - Smaller contributions from ttV and tH
- Data-driven multijet estimation:
  - Tag rate function TRF_{MJ} extracted in 2b-tag region
  - Allows to emulate multijet backgr. versus nr. of b-tags
  - Validated with closure test in data and MC
- Employs BDT discriminants in each category

	2 b-tags	3 b-tags	4 b-tags
6 jets	Used to extract multijet backg.	BDT control	BDT control
7 jets		BDT signal	BDT signal
≥8 jets		BDT signal	BDT signal



Process	σ [pb]
$t\bar{t}H$	$0.129^{+0.012}_{-0.016}$
$t\bar{t}$	253^{+13}_{-15}
Single top Wt-channel	22.4 ± 1.5
Single top t-channel	$87.7^{+3.4}_{-1.9}$
Single top s-channel	5.61 ± 0.22
$t\bar{t} + W$	0.232 ± 0.070
$t\bar{t} + Z$	0.205 ± 0.061
$tHqb$	$0.0172^{+0.0012}_{-0.0011}$
WtH	$0.0047^{+0.0010}_{-0.0009}$



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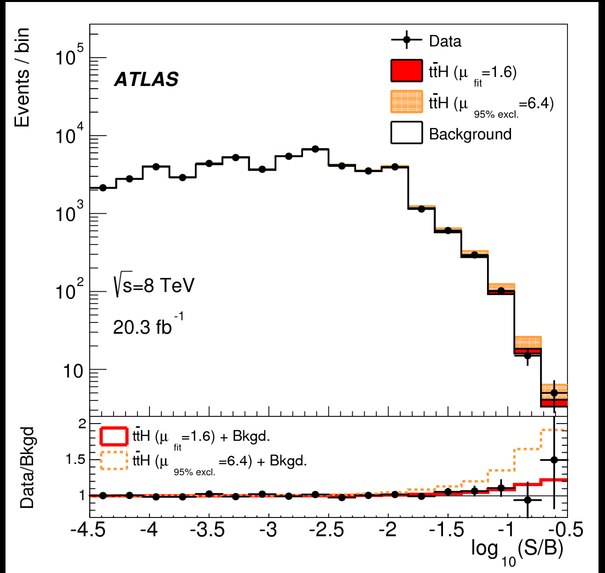
Results

- Profile likelihood fit to BDT output in 6 regions
  - Determine signal strength $\mu = \sigma_{obs.}/\sigma_{SM}$
  - Constrains normalization of each background as nuisance parameter
  - Multijet background free parameter (like μ but unlike simulated backgrounds)
- Fit results:
  - Best fit μ = 1.6 ± 2.6
  - Limits at 95% CL: μ < 6.4 (expected 5.4)



	6j, 3b	6j, ≥4b	7j, 3b	7j, ≥4b	≥8j, 3b	≥8j, ≥4b
Multijet	16380 ± 130	1112 ± 33	12530 ± 110	1123 ± 34	10670 ± 100	1324 ± 36
$t\bar{t}$+light	1530 ± 390	48 ± 18	1370 ± 430	45 ± 18	1200 ± 520	40 ± 23
$t\bar{t}+c\bar{c}$	280 ± 180	17 ± 12	390 ± 240	21 ± 15	560 ± 350	48 ± 33
$t\bar{t}+b\bar{b}$	330 ± 180	44 ± 26	490 ± 270	87 ± 51	760 ± 450	190 ± 110
$t\bar{t}+V$	14.2 ± 6.3	1.8 ± 1.5	22.0 ± 9.0	3.5 ± 2.3	40 ± 15	8.0 ± 4.2
Single top	168 ± 63	6.0 ± 3.7	139 ± 55	8.3 ± 4.6	110 ± 49	10.6 ± 5.9
Total background	18700 ± 480	1229 ± 48	14940 ± 580	1288 ± 66	13330 ± 780	1620 ± 130
$t\bar{t}H$ (m_H=125 GeV)	14.3 ± 4.6	3.3 ± 2.1	23.7 ± 6.4	7.2 ± 3.3	48 ± 11	16.8 ± 6.1
Data events	18508	1545	14741	1402	13131	1587
S/B	¡ 0.001	0.003	0.002	0.006	0.004	0.010
$S/\sqrt{B}$	0.10	0.095	0.194	0.20	0.415	0.417

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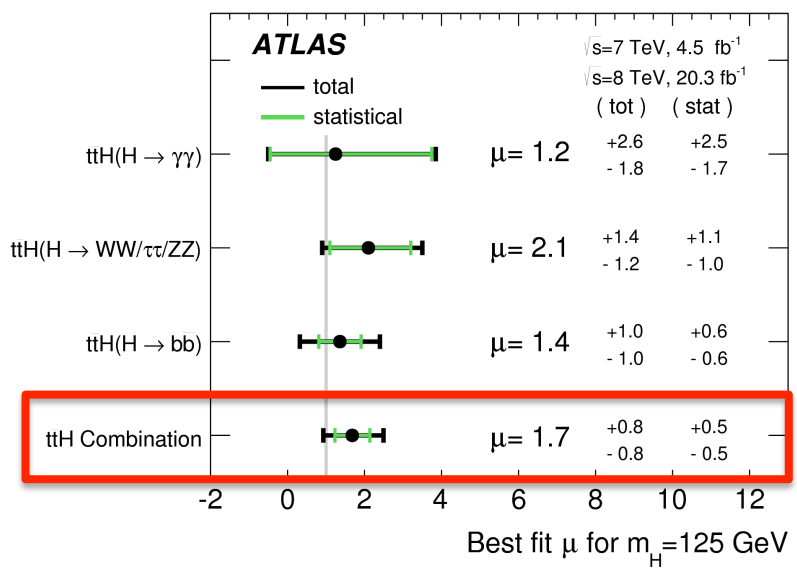
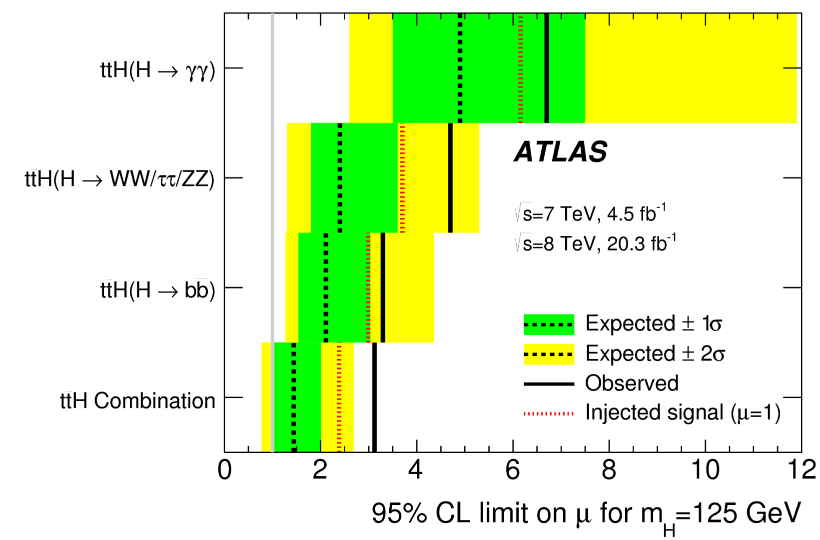
ttH combination

- ATLAS combined all above analyses to get final LHC Run 1 sensitivity
- LHC Run 1 ATLAS best fit: $\mu_{ttH} = 1.7 \pm 0.8$
- Compatible with SM signal ($\mu_{ttH} = 1$) within 1σ
- 2σ above $\mu_{ttH} = 0$ (background-only hypothesis)
- 95% CL limit: $\mu_{ttH} < 3.1 \times$ SM (obs) / $1.4 \times$ SM (exp)

Representative/best analysis category

ttH channel	S/B	S/√B
H→γγ	64%	0.6
multilepton	20%	0.69
H→bb 1ℓ	4%	0.8
H→bb 2ℓ	6%	0.4
H→bb all-had.	1%	0.4



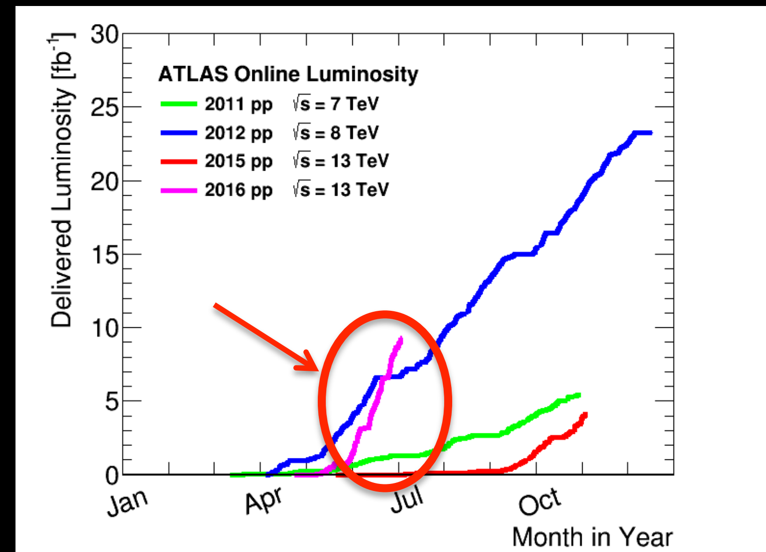


Conclusions and outlook

- ttH production provides unique, direct access to top Yukawa coupling and Higgs properties
  - Covered H→γγ, H→WW, H→ττ, H→ZZ, H→bb decay channels
- Combined signal strength 2σ above background-only hypothesis and compatible with SM expectations

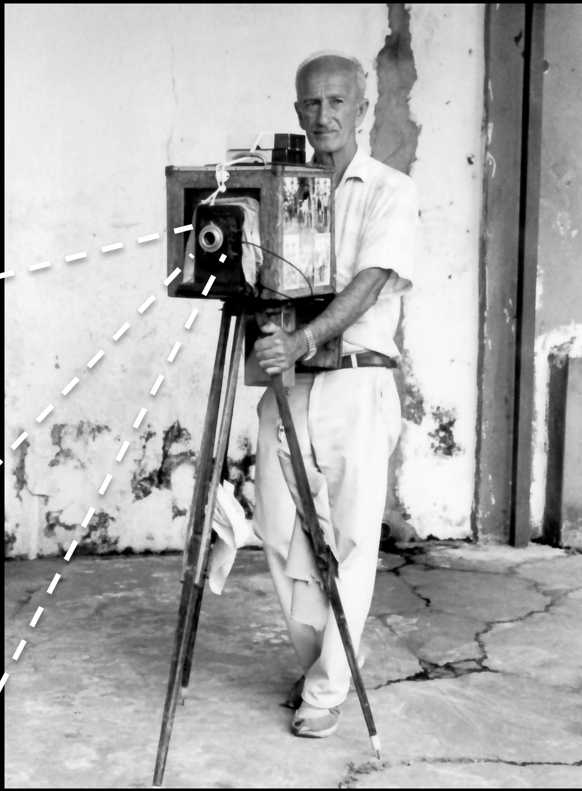
$$\mu_{ttH} = 1.7 \pm 0.8$$

- Better sensitivity expected soon :
  - Higher luminosity (ramping up quickly!)
  - Better S/B ratio(*) with respect to some backgrounds

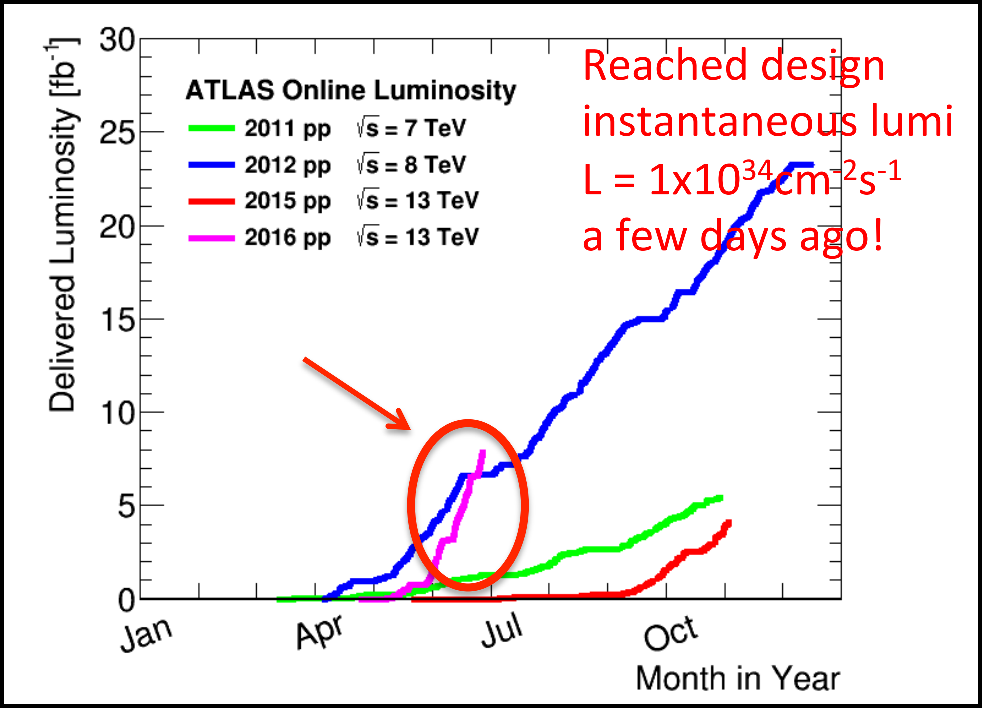


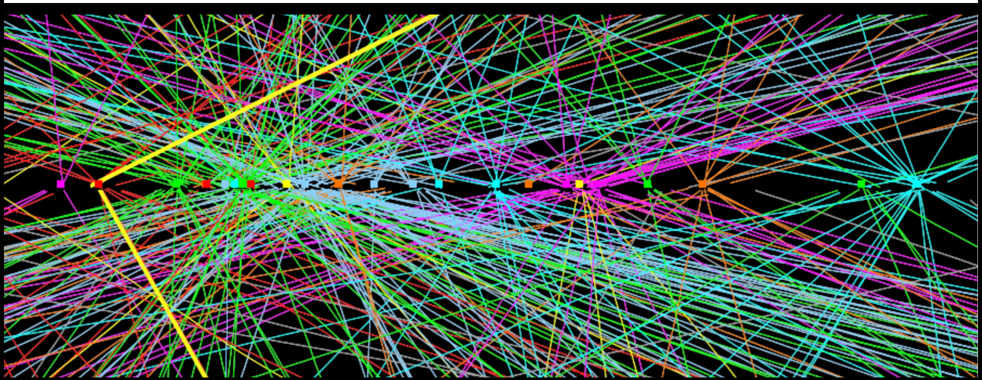
(*) Before cuts and for inclusive tt+jets; not necessarily true after cuts for all channels and jet flavours

Bonus slides



LHC and ATLAS Performance





Run 2 at 13 TeV (**so far!...**):

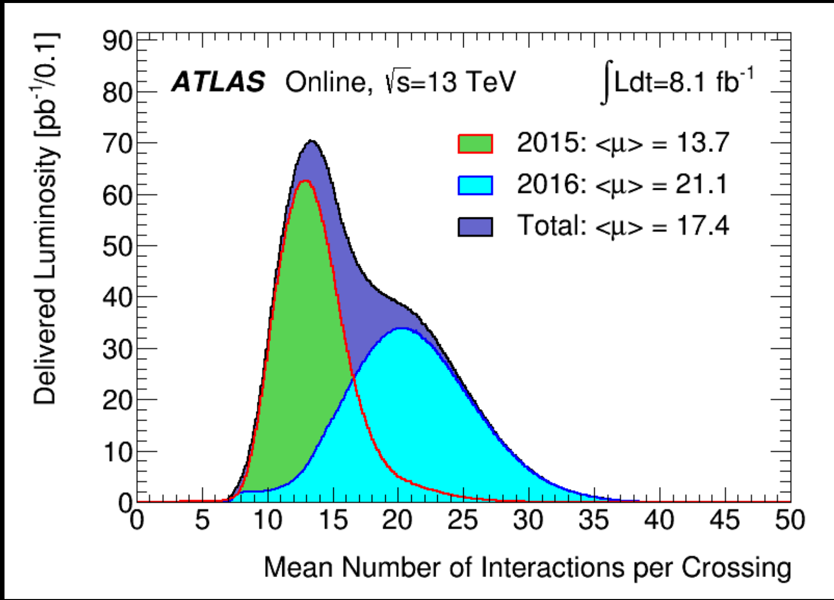
$9.4 \times 10^{33} cm^{-2}s^{-1}$ peak luminosity

Up to ≈40 pileup interactions

≈91% efficiency after physics-quality data requirements

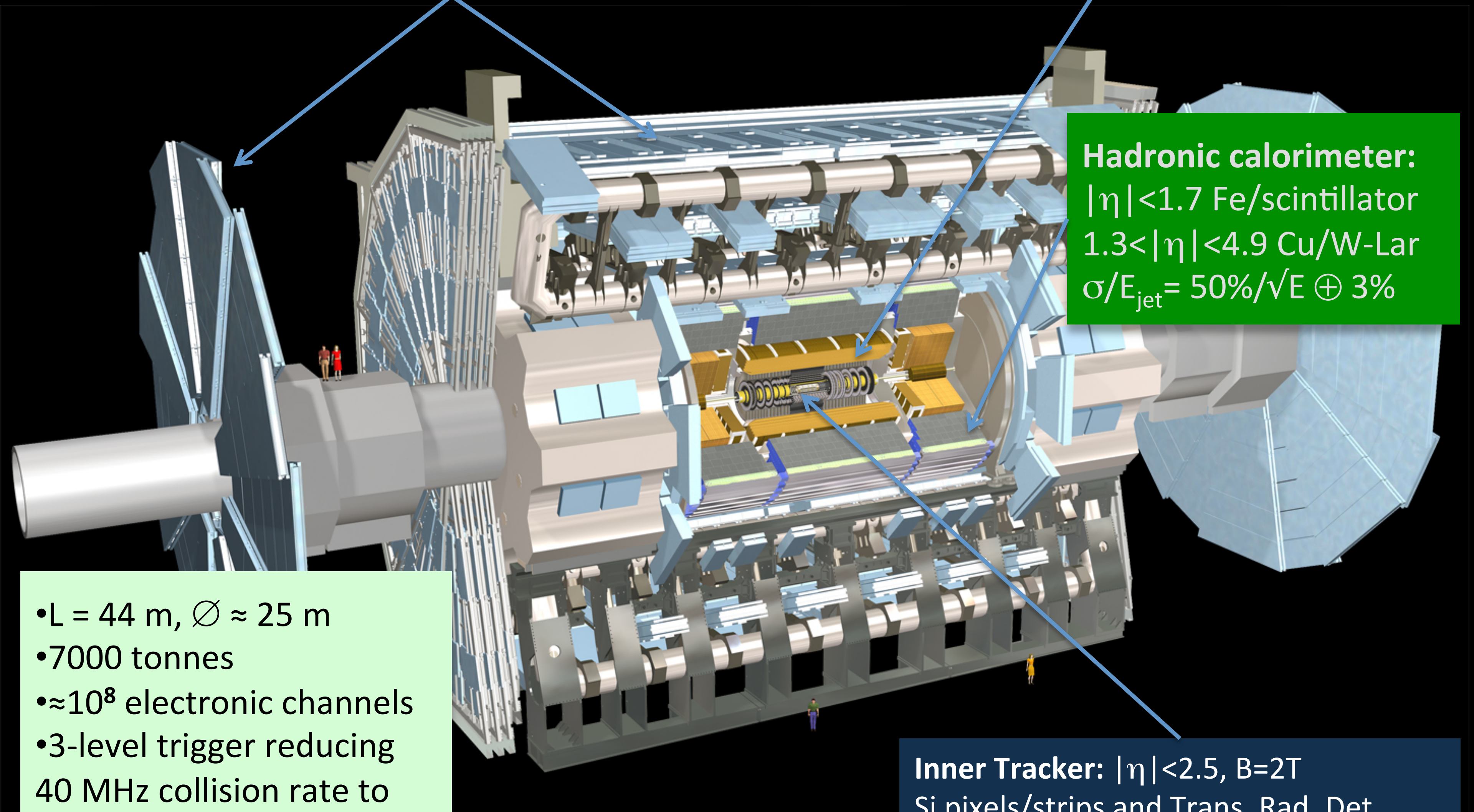
5.96 fb^{-1} recorded so far in 2016

3.2 fb^{-1} physics data in 2015



Muon Spectrometer: $|\eta|<2.7$
Air-core toroids and gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

EM calorimeter: $|\eta|<3.2$
Pb-LAr Accordion
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$



Hadronic calorimeter:
$|\eta|<1.7$ Fe/scintillator
$1.3<|\eta|<4.9$ Cu/W-Lar
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$

- L = 44 m, ∅ ≈ 25 m
- 7000 tonnes
- ≈10^8 electronic channels
- 3-level trigger reducing 40 MHz collision rate to 200 Hz of events to tape

Inner Tracker: $|\eta|<2.5$, B=2T
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\text{GeV}) \oplus 1\%$

$t\bar{t}H$, H→γγ Backup

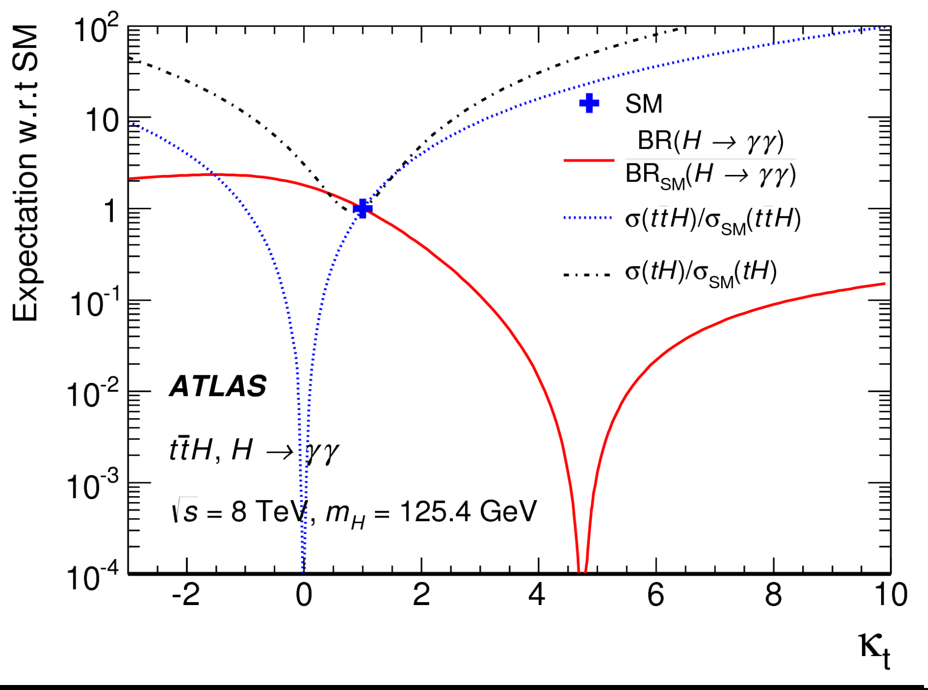
Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH	N_B
7 TeV leptonic selection	0.10	0.6	0.1	14.9	4.0	72.6	5.3	2.5	$0.5^{+0.5}_{-0.3}$
7 TeV hadronic selection	0.07	10.5	1.3	1.3	1.4	80.9	2.6	1.9	$0.5^{+0.5}_{-0.3}$
8 TeV leptonic selection	0.58	1.0	0.2	8.1	2.3	80.3	5.6	2.6	$0.9^{+0.6}_{-0.4}$
8 TeV hadronic selection	0.49	7.3	1.0	0.7	1.3	84.2	3.4	2.1	$2.7^{+0.9}_{-0.7}$

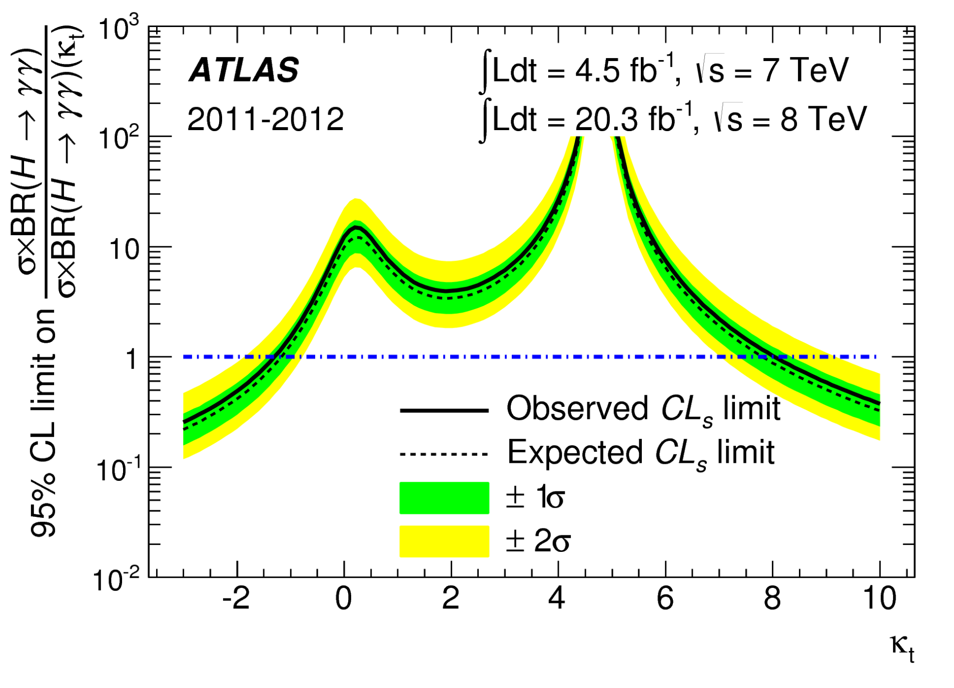
- Summary of systematic uncertainties on the final yield of events for 7 TeV data from $t\bar{t}H$, tHqb and WtH production after applying the leptonic and hadronic selection requirements. The uncertainties for the dominant H → γγ processes without top quarks in the hadronic category, ggF, and in the leptonic category, WH, are also shown. For both tH production processes, the maximum uncertainty observed for all values of κ_t generated (+1, 0, -1) is reported. For branching fraction and cross section uncertainties which depend on mH, the numbers at mH = 125 GeV are quoted.

	$t\bar{t}H$ [%]		tHqb [%]		WtH [%]		ggF [%]	WH [%]
	had.	lep.	had.	lep.	had.	lep.	had.	lep.
Luminosity	±1.8							
Photons	±10.0	±10.0	±10.0	±10.0	±10.0	±10.0	±10.0	±10.0
Leptons	< 0.1	±0.7	< 0.1	±0.7	< 0.1	±0.6	< 0.1	±0.7
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±9.1	±1.6	±19	±2.4	±13	±2.9	±30	±10
Bkg. modeling	0.12 evt.	0.01 evt.	applied on the sum of all Higgs boson production processes					
Theory ($\sigma \times$ BR)	+10,−13		+8,−7		+12,−12		+11,−12	+5.5,−5.5
MC Modeling	±11	±3.3	±12	±4.4	±13	±5.2	±130	±100

ttH, H→γγ backup

- $y_{top} = \kappa_t \, y_{top}^{SM}$
- Analysis sensitive to ttH and tH:
  - ttH cross section zero if $\kappa_t = 0$
  - BR(H→γγ) zero if W and t contribution to H→γγ cancel
  - tH cross section more complicated: only 1 of 3 diagrams at tree level
- 95% CL limits on (σ x BR x dependence on κ_t) give limits on κ_t

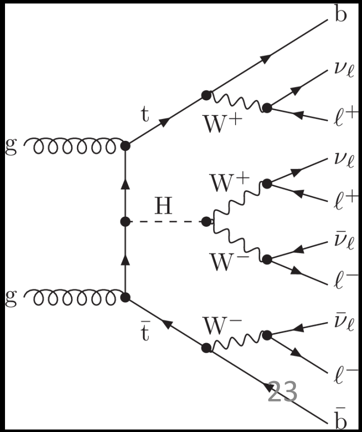




Multilepton backup

Process	ME Generator	Parton Shower	PDF	Tune
$t\bar{t}H$	HELAC-Oneloop [41, 42] + POWHEG-BOX [48-50]	PYTHIA 8 [43]	CT10 [44]/CTEQ6L1 [45, 46]	AU2 [47]
$tHqb$	MADGRAPH [33]	PYTHIA 8	CT10	AU2
tHW	MG5_aMC@NLO [29]	HERWIG++ [51]	CT10/MRST LO** [52]	UE-EE-4 [53]
$t\bar{t}W + \leq 2$ partons	MADGRAPH	PYTHIA 6 [54]	CTEQ6L1	AUET2B [55]
$t\bar{t}(Z/\gamma^*) + \leq 1$ parton	MADGRAPH	PYTHIA 6	CTEQ6L1	AUET2B
$t(Z/\gamma^*)$	MADGRAPH	PYTHIA 6	CTEQ6L1	AUET2B
$q\bar{q}, qg \to WW, WZ$	SHERPA [56]	SHERPA	CT10	SHERPA default
$qq \to qqWW, qqWZ, qqZZ$	SHERPA	SHERPA	CT10	SHERPA default
$q\bar{q}, qg \to ZZ$	POWHEG-BOX [57]	PYTHIA 8	CT10	AU2
$gg \to ZZ$	GG2ZZ [58]	HERWIG [59]	CT10	AUET2 [60]
$t\bar{t}$	POWHEG-BOX [61]	PYTHIA 6	CT10/CTEQ6L1	Perugia2011C [62]
s-, t-channel, Wt single top	POWHEG-BOX [63, 64]	PYTHIA 6	CT10/CTEQ6L1	Perugia2011C
$Z \to \ell^+\ell^- + \leq 5$ partons	ALPGEN [65]	PYTHIA 6	CTEQ6L1	Perugia2011C
$W \to \ell\nu + \leq 5$ partons	ALPGEN	PYTHIA 6	CTEQ6L1	Perugia2011C

Channel	Observed Limit	Expected Limit -2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Median ($\mu = 1$)
$2\ell 0\tau_{\text{had}}$	6.7	2.1	2.8	3.9	5.7	8.4	5.0
3ℓ	6.8	2.0	2.7	3.8	5.7	8.5	5.1
$2\ell 1\tau_{\text{had}}$	7.5	4.5	6.1	8.4	13	21	10
4ℓ	18	8.0	11	15	23	39	17
$1\ell 2\tau_{\text{had}}$	13	10	13	18	26	40	19
Combined	4.7	1.3	1.8	2.4	3.6	5.3	3.7



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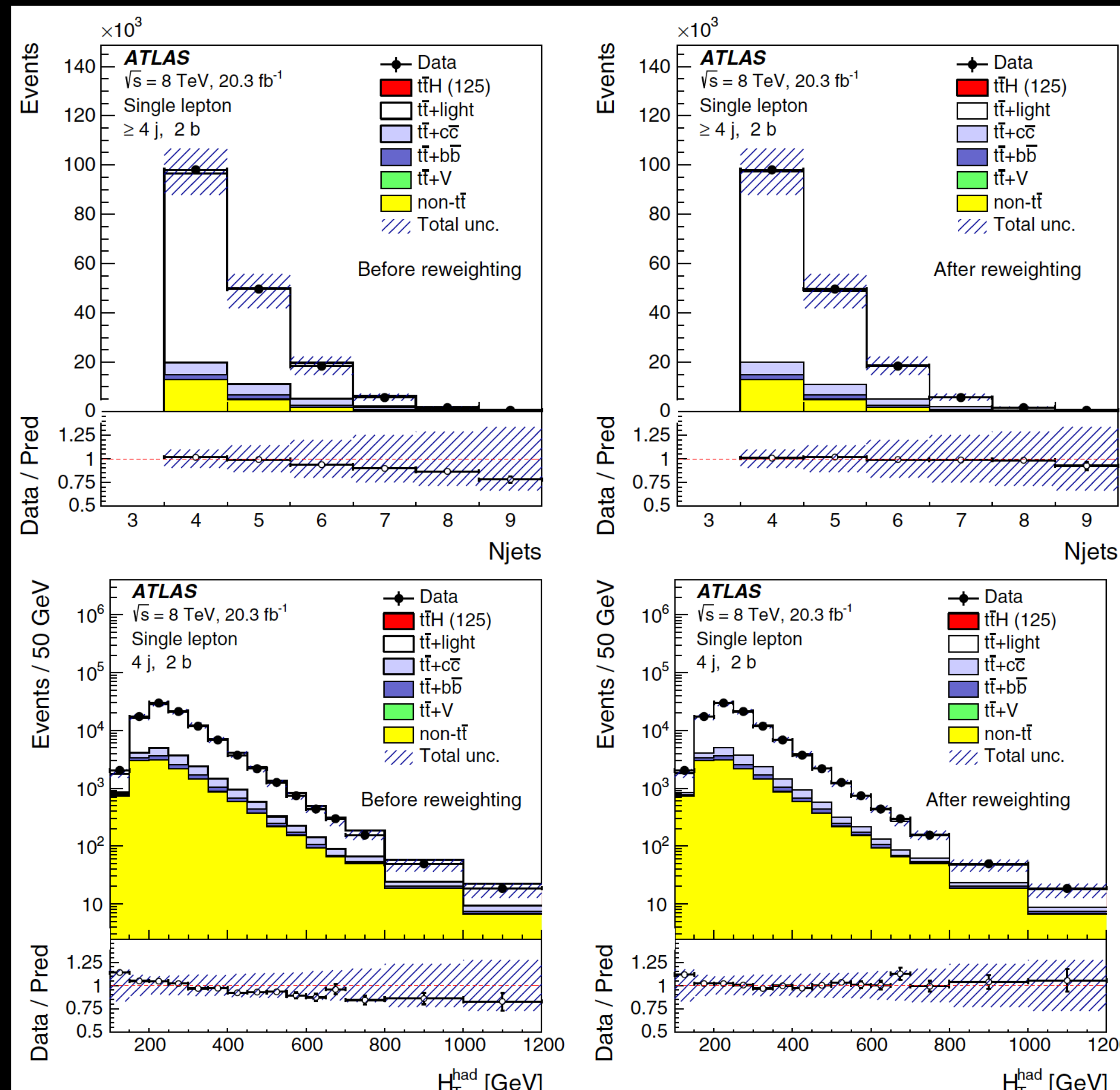
Multilepton event selection

Cat.	Light leptons	Taus	jets	Other
$2\ell 0\tau_{had}$	2 same-sign e/μ p_T > 25/20 GeV $\|\eta_e\|$<1.37 => charge rec.	none	≥ 4 jets ≥ 1 *b* tag => suppress tt+jets and ttW	**6 subcategories** of: N_{lepton} ($e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$) x N_{jet} (==4, ≥5)
3ℓ	3 $e^{\pm}$ or $\mu^{\pm}$ total charge ±1 p_T > 20 GeV same-sign e/μ pair => non-prompt BG	any	3 jets + ≥ 2 *b* tags or ≥ 4 jets + 1 *b* => suppress tt+jets and ttV	$\|m_{ee/\mu\mu} - m_Z\|$ > 10 GeV => suppress ttZ
$2\ell 1\tau_{had}$	2 same-sign e/μ p_T > 25/15 GeV	1 τ_{had} p_T > 25GeV	≥ 4 jets => suppress ttV and tt + jets ≥ 1 b tag => suppress V and VV prod	$\|m_{ee/\mu\mu} - m_Z\|$ > 10 GeV => suppress Z + jets
4ℓ	4 $e^{\pm}$ or $\mu^{\pm}$ zero total charge p_T > 25/15 GeV for leading light leptons	any	≥ 2 jets, ≥ 1 b tag => suppress tt +jets and ttW => suppress ttV and tt + jets	$\|m_{ee/\mu\mu} - m_Z\|$ > 10 GeV => suppress ttZ 100 < $m_{4\,lep}$< 500 GeV => suppress Z → 4ℓ, ttZ 2 categories: Z-enriched (ee/μμ pair) and Z-depleted
$1\ell 2\tau_{had}$	1 e or μ p_T > 25 GeV	2 τ_{had} opposite charge	≥ 3 jets => suppress ttV and tt + jets ≥ 1 b tag => suppress V and VV production	60 < m_{vis} (ττ) < 120 GeV => target H → ττ

H→bb: Background modeling

tt+jets modeling:

- tt+bb MC reweighted from Sherpa OpenLoops prediction
  - Fully ME+PS matched (MLM)
  - NLO prediction
  - Massive b quarks (4 Flavour Scheme)
  - CT10 PDF set
- tt+light jets and tt+cc reweighted
  - As function of $p_T(tt)$
  - As function of top quark p_T
  - To correct Data/MC difference found in 7 TeV differential cross section
    - Checked validity in simulation
- After reweighting, Data/MC agreement clearly improved



Single-lepton H→bb – variable ranking

Variable	Definition	NN rank			
		$\geq 6j, \geq 4b$	$\geq 6j$, 3b	$5j, \geq 4b$	5j, 3b
$D1$	Neyman–Pearson MEM discriminant (Eq. (4))	1	10	-	-
Centrality	Scalar sum of the p_T divided by sum of the E for all jets and the lepton	2	2	1	-
p_T^{jet5}	p_T of the fifth leading jet	3	7	-	-
$H1$	Second Fox–Wolfram moment computed using all jets and the lepton	4	3	2	-
ΔR_{bb}^{avg}	Average ΔR for all b-tagged jet pairs	5	6	5	-
SSLL	Logarithm of the summed signal likelihoods (Eq. (2))	6	4	-	-
$m_{bb}^{min\ \Delta R}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	7	12	4	4
$m_{bj}^{max\ p_T}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_T	8	8	-	-
$\Delta R_{bb}^{max\ p_T}$	ΔR between the two b-tagged jets with the largest vector sum p_T	9	-	-	-
$\Delta R_{lep-bb}^{min\ \Delta R}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	10	11	10	-
$m_{uu}^{min\ \Delta R}$	Mass of the combination of the two untagged jets with the smallest ΔR	11	9	-	2
$Aplan_{b-jet}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor[92] built with only b-tagged jets	12	-	8	-
N_{40}^{jet}	Number of jets with $p_T \geq 40 GeV$	-	1	3	-
$m_{bj}^{min\ \Delta R}$	Mass of the combination of a b-tagged jet and any jet with the smallest ΔR	-	5	-	-
$m_{jj}^{max\ p_T}$	Mass of the combination of any two jets with the largest vector sum p_T	-	-	6	-
H_T^{had}	Scalar sum of jet p_T	-	-	7	-
$m_{jj}^{min\ \Delta R}$	Mass of the combination of any two jets with the smallest ΔR	-	-	9	-
$m_{bb}^{max\ p_T}$	Mass of the combination of the two b-tagged jets with the largest vector sum p_T	-	-	-	1
$p_{T,uu}^{min\ \Delta R}$	Scalar sum of the p_T of the pair of untagged jets with the smallest ΔR	-	-	-	3
$m_{bb}^{max\ m}$	Mass of the combination of the two b-tagged jets with the largest invariant mass	-	-	-	5
$\Delta R_{uu}^{min\ \Delta R}$	Minimum ΔR between the two untagged jets	-	-	-	6
m_{jjj}	Mass of the jet triplet with the largest vector sum p_T	-	-	-	7

Dilepton H→bb – variable ranking

Variable	Definition	NN rank		
		$\geq$ 4j, $\geq$ 4b	$\geq$ 4j, 3b	3j, 3b
$\Delta\eta_{\mathrm{jj}}^{\mathrm{max}\ \Delta\eta}$	Maximum $\Delta\eta$ between any two jets in the event	1	1	1
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta \mathrm{R}}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	2	8	-
$m_{b\bar{b}}$	Mass of the two b-tagged jets from the Higgs candidate system	3	-	-
$\Delta R_{\mathrm{hl}}^{\mathrm{min}\ \Delta \mathrm{R}}$	ΔR between the Higgs candidate and the closest lepton	4	5	-
$\mathrm{N}_{30}^{\mathrm{Higgs}}$	Number of Higgs candidates within 30 GeV of the Higgs mass of 125 GeV	5	2	5
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	6	4	8
$\mathrm{Aplan}_{\mathrm{jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with all jets	7	7	-
$m_{\mathrm{jj}}^{\mathrm{min}\ \mathrm{m}}$	Minimum dijet mass between any two jets	8	3	2
$\Delta R_{\mathrm{hl}}^{\mathrm{max}\ \Delta \mathrm{R}}$	ΔR between the Higgs candidate and the furthest lepton	9	-	-
$m_{\mathrm{jj}}^{\mathrm{closest}}$	Dijet mass between any two jets closest to the Higgs mass of 125 GeV	10	-	10
H_{T}	Scalar sum of jet p_{T} and lepton p_{T} values	-	6	3
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{m}}$	ΔR between the two b-tagged jets with the largest invariant mass	-	9	-
$\Delta R_{\mathrm{lj}}^{\mathrm{min}\ \Delta \mathrm{R}}$	Minimum ΔR between any lepton and jet	-	10	-
Centrality	Sum of the p_{T} divided by sum of the E for all jets and both leptons	-	-	7
$m_{\mathrm{jj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of any two jets with the largest vector sum p_{T}	-	-	9
$H4$	Fifth Fox–Wolfram moment computed using all jets and both leptons	-	-	4
$p_{\mathrm{T}}^{\mathrm{jet3}}$	p_{T} of the third leading jet	-	-	6

Dilepton + single-lepton H→bb Systematics

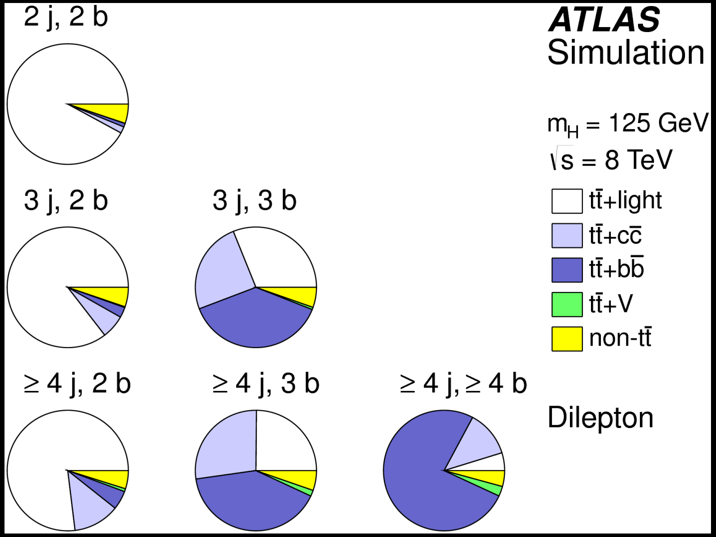
- List of systematic uncertainties considered. An "N" means that the uncertainty is taken as normalisation-only for all processes and channels affected, whereas an "S" denotes systematic uncertainties that are considered shape-only in all processes and channels. An "SN" means that the uncertainty is taken on both shape and normalisation. Some of the systematic uncertainties are split into several components for a more accurate treatment. This is the number indicated in the column labelled as "Comp.”

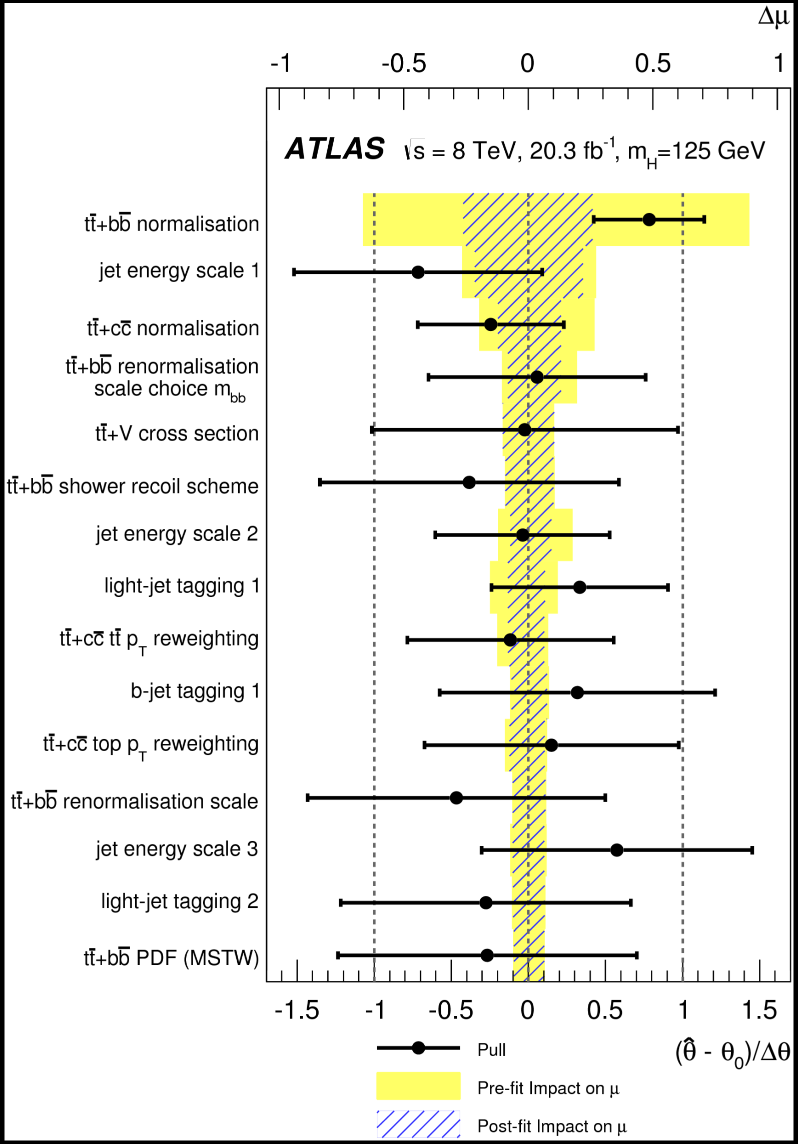
Systematic uncertainty	Type	Comp.
Luminosity	N	1
Physics Objects		
Electron	SN	5
Muon	SN	6
Jet energy scale	SN	22
Jet vertex fraction	SN	1
Jet energy resolution	SN	1
Jet reconstruction	SN	1
b-tagging efficiency	SN	6
c-tagging efficiency	SN	4
Light-jet tagging efficiency	SN	12
High-p_{T} tagging efficiency	SN	1
Background Model		
$t\bar{t}$ cross section	N	1
$t\bar{t}$ modelling: p_{T} reweighting	SN	9
$t\bar{t}$ modelling: parton shower	SN	3
$t\bar{t}$+heavy-flavour: normalisation	N	2
$t\bar{t}+c\bar{c}$: p_{T} reweighting	SN	2
$t\bar{t}+c\bar{c}$: generator	SN	4
$t\bar{t}+b\bar{b}$: NLO Shape	SN	8
W+jets normalisation	N	3
W p_{T} reweighting	SN	1
Z+jets normalisation	N	3
Z p_{T} reweighting	SN	1
Lepton misID normalisation	N	3
Lepton misID shape	S	3
Single top cross section	N	1
Single top model	SN	1
Diboson+jets normalisation	N	3
$t\bar{t}+V$ cross section	N	1
$t\bar{t}+V$ model	SN	1
Signal Model		
$t\bar{t}H$ scale	SN	2
$t\bar{t}H$ generator	SN	1
$t\bar{t}H$ hadronisation	SN	1
$t\bar{t}H$ PDF	SN	1

Dilepton + single-lepton H→bb

- The fitted values of the nuisance parameters with the largest impact on the measured signal strength. The points, which are drawn conforming to the scale of the bottom axis, show the deviation of each of the fitted nuisance parameters, hat{θ}, from θ_0, which is the nominal value of that nuisance parameter, in units of the pre-fit standard deviation Δθ. The error bars show the post-fit uncertainties, σ_θ, which are close to 1 if the data do not provide any further constraint on that uncertainty. Conversely, a value of σ_θ much smaller than 1 indicates a significant reduction with respect to the original uncertainty. The nuisance parameters are sorted according to the post-fit effect of each on μ (hashed blue area) conforming to the scale of the top axis, with those with the largest impact at the top.

Dilepton





Matrix Element Method

$$P_i(\boldsymbol{x}|\boldsymbol{\alpha}) = \frac{(2\pi)^4}{\sigma_i^{\text{exp}}(\boldsymbol{\alpha})} \int \mathrm{d}p_A \mathrm{d}p_B\, f(p_A)\, f(p_B)\, \frac{|\mathcal{M}_i(\boldsymbol{y}|\boldsymbol{\alpha})|^2}{\mathcal{F}}\, W(\boldsymbol{y}|\boldsymbol{x})\, \mathrm{d}\Phi_N(\boldsymbol{y})$$

P_i = probability density of event with reco 4-momenta x coming from process i with parameters α

M_i = matrix element for process i with parton-level 4-momenta y – assume H→bb

$W(y,x)$ = transfer functions mapping 4-momenta y to reconstruction level x – assume δ function

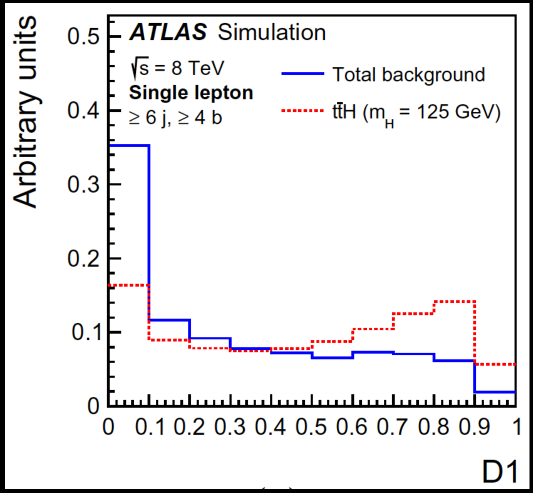
$d\Phi_N$ = phase space integration element

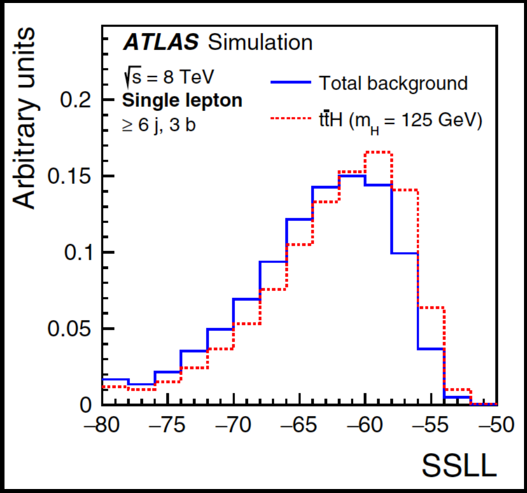
$\sigma_i^{exp}(\alpha)$ = cross section x acceptance x efficiency (to normalize P_i)

- Process likelihood: sum probabilities for each permutation of final state particles (assignment ambiguity)
- Calculate likelihood ratio D1 of H→bb signal and tt+bb background (with α a norm. factor)

$$\mathcal{L}_i(\boldsymbol{x}|\boldsymbol{\alpha}) = \sum_{p=1}^{N_p} P_i^p(\boldsymbol{x}|\boldsymbol{\alpha})$$

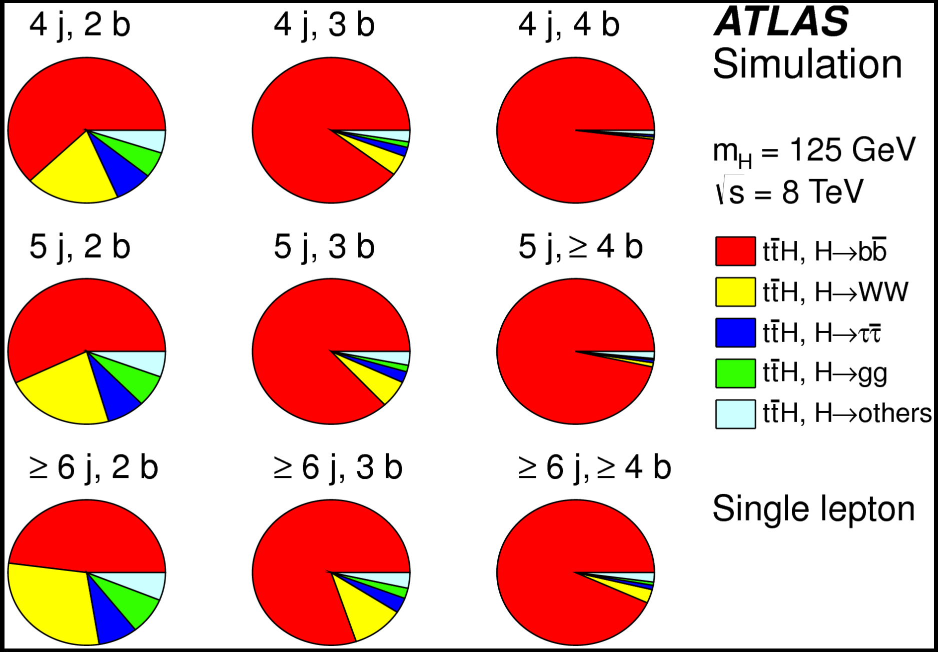
$$D1 = \frac{\mathcal{L}_{t\bar{t}H}}{\mathcal{L}_{t\bar{t}H} + \alpha \cdot \mathcal{L}_{t\bar{t}+b\bar{b}}}$$

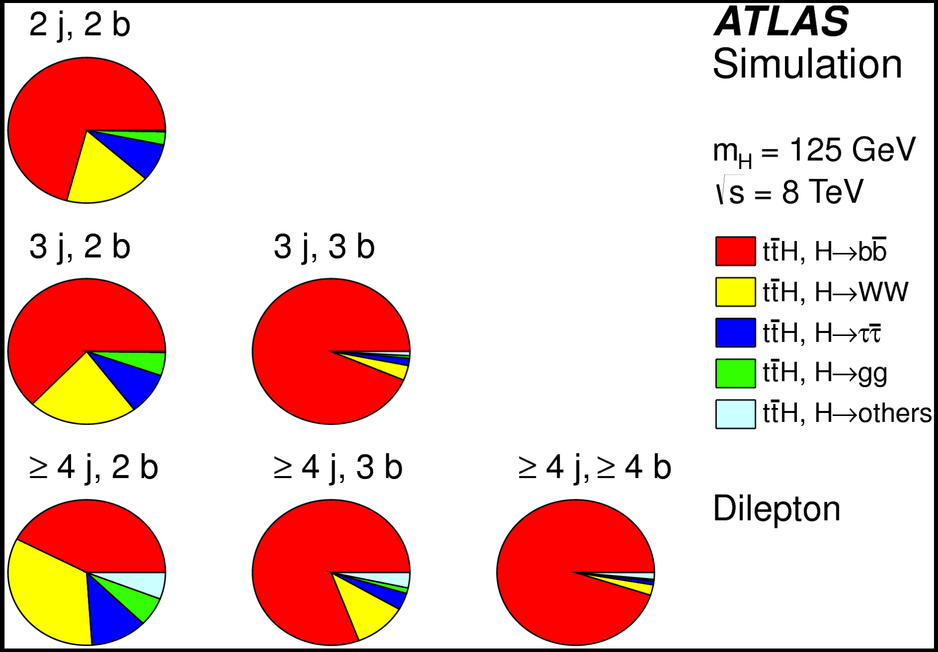




SSLL = log of summed signal likelihoods

Dilepton + single-lepton H→bb





All-hadronic ttH, H→bb

	6j, 3b	6j, ≥4b	7j, 3b	7j, ≥4b	≥8j, 3b	≥8j, ≥4b
Multijet	16380 ± 130	1112 ± 33	12530 ± 110	1123 ± 34	10670 ± 100	1324 ± 36
$t\bar{t}$+light	1530 ± 390	48 ± 18	1370 ± 430	45 ± 18	1200 ± 520	40 ± 23
$t\bar{t} + c\bar{c}$	280 ± 180	17 ± 12	390 ± 240	21 ± 15	560 ± 350	48 ± 33
$t\bar{t} + b\bar{b}$	330 ± 180	44 ± 26	490 ± 270	87 ± 51	760 ± 450	190 ± 110
$t\bar{t} + V$	14.2 ± 6.3	1.8 ± 1.5	22.0 ± 9.0	3.5 ± 2.3	40 ± 15	8.0 ± 4.2
Single top	168 ± 63	6.0 ± 3.7	139 ± 55	8.3 ± 4.6	110 ± 49	10.6 ± 5.9
Total background	18700 ± 480	1229 ± 48	14940 ± 580	1288 ± 66	13330 ± 780	1620 ± 130
$t\bar{t}H$ (m_H=125 GeV)	14.3 ± 4.6	3.3 ± 2.1	23.7 ± 6.4	7.2 ± 3.3	48 ± 11	16.8 ± 6.1
Data events	18508	1545	14741	1402	13131	1587
S/B	¡ 0.001	0.003	0.002	0.006	0.004	0.010
$S/\sqrt{\mathrm{B}}$	0.10	0.095	0.194	0.20	0.415	0.417

Variable	Definition	BDT rank					
		6j, 3b	6j, ≥ 4b	7j, 3b	7j, ≥ 4b	≥ 8j, 3b	≥ 8j, ≥ 4b
$\mathrm{Centrality}_{\mathrm{Mass}}$	Scalar sum of the jet p_{T} divided by the invariant mass of the jets	1	1	1	1	9	6
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with all jets	–	11	–	–	6	–
S_{T}	The modulus of the vector sum of jet p_{T}	2	2	2	4	2	2
$H_{\mathrm{T}\,5}$	Scalar sum of jet p_{T} starting from the fifth jet	8	–	–	7	–	–
m_{jj}^{min}	Smallest invariant mass of any combination of two jets	9	–	6	10	11	12
ΔR^{min}	Minimum ΔR between two jets	6	5	9	–	8	4
$p_{\mathrm{T}}^{\mathrm{softest\ jet}}$	p_{T} of the softest jet	–	6	10	–	–	10
$\Delta R(b,b)^{p_{\mathrm{T}}^{\mathrm{max}}}$	ΔR between two b-tagged jets with the largest vector sum p_{T}	11	–	7	5	5	3
$m_{bb}^{\Delta R(b,b)^{\mathrm{min}}}$	Invariant mass of the combination of two b-tagged jets with the smallest ΔR	3	3	8	9	3	9
$\frac{E_{\mathrm{T}\,1}+E_{\mathrm{T}\,2}}{\sum E_{\mathrm{T}}^{\mathrm{jets}}}$	Sum of the E_{T} of the two jets with leading E_{T} divided by the sum of the E_{T} of all jets	5	8	4	2	7	5
$m_{2\,\mathrm{jets}}$	The mass of the dijet pair, which, when combined with any b-tagged jet, maximises the magnitude of the vector sum of the p_{T} of the three-jet system	10	–	–	8	–	–
$m_{2\,\mathrm{b-jets}}$	The invariant mass of the two b-tagged jets which are selected by requiring that the invariant mass of all the remaining jets is maximal	12	7	–	6	–	8
$m_{\mathrm{top},1}$	Mass of the reconstructed top quark	13	10	–	–	4	11
$m_{\mathrm{top},2}$	Mass of the reconstructed top quark calculated from the jets not entering $m_{\mathrm{top},1}$	7	9	5	–	10	7
Λ	The logarithm of the ratio of event probabilities under the signal and background hypotheses	4	4	3	3	1	1

Event reconstruction

- Electrons:
  - From charged tracks and electromagnetic calorimeter energy clusters for $p_T >$ 10 GeV
  - Typically $|\eta|<2.47$; may also reject barrel-endcap transition $1.37<|\eta|<1.52$
  - Isolation cuts on additional E_T within $\Delta R = \sqrt{(\Delta\phi^2+\Delta\eta^2)} = 0.2$ of electron candidate must be $< 0.05 \times E_T^e$ – measured in both calorimeter and tracks
  - Check track longitudinal and transverse impact parameters wrt event primary vertex

- Muons:
  - From combining inner-detector charged tracks with muon-spectrometer tracks of segments for $p_T > 10$ GeV and $|\eta|<2.50$
  - Isolation cuts of $\Delta R > 0.04+(10\text{GeV})/p_T^\mu$ from nearest jet
  - Check track longitudinal and transverse impact parameters wrt event primary vertex

- Hadronically-decaying taus (τ_{had}):
  - Combine calorimeter clusters and 1 or 3 inner-detector charged tracks (total charge ±1) for $p_T > 25$ GeV and $|\eta|<2.47$
  - Identification using two Boosted Decision Trees (BDT) to reject fake taus

Event reconstruction

- Jets in multilepton analysis:
  - Built within |η|<4.9 from calibrated calorimeter clusters with the anti-k_T algorithm with R parameter 0.4
  - Calibrated with (simulation based) factors and in-situ corrections for data/simulation differences
  - Typical cuts are p_T > 25 GeV; |η|<2.47 if requiring b-tagging
  - Pileup-cleaning: jets with p_T < 50 GeV rejected if >50% of their track-based p_T not from primary vertex

- B-tagging:
  - Jets containg b-hadrons identified with multivariate discriminant combining track impact parameters with information from displaced decay vertices within jets
  - Typical algorithm tunes give efficiencies of 70% with mis-tag rates of around 1% for light-quark jets and 20% for c-hadrons
  - Other working points: b-tagging efficiency of 60%, 80% and 85%
  - Algorithm efficiency and mis-tag rates calibrated based on data measurements

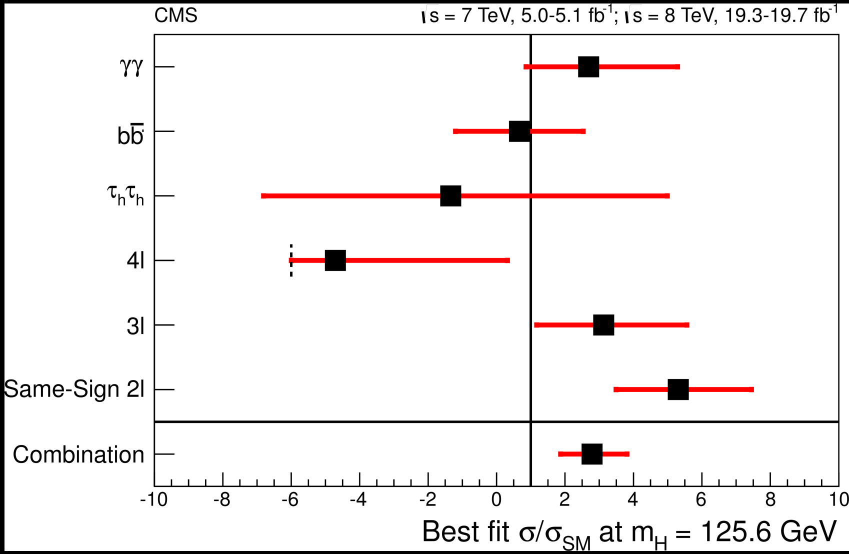
Event reconstruction

- Missing E_T:
  - Calculated from calorimeter clusters
  - Corrections are applied to identified photons, electrons, muons, and jets

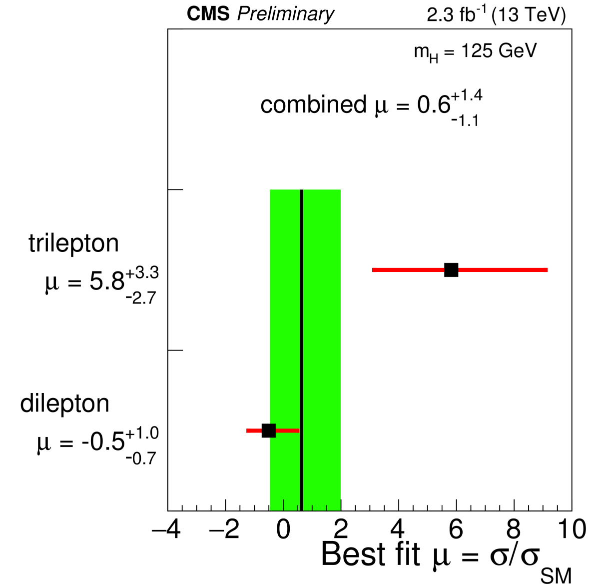
- Photons in $H \rightarrow \gamma\gamma$ analysis:
  - From electromagnetic calorimeter energy clusters for $p_T > 10$ GeV
  - May match one or two tracks
  - Different energy calibration depends for clusters with tracks
  - Typically $|\eta|<2.37$ rejecting barrel-endcap transition $1.37<|\eta|<1.52$
  - Isolation cut on track p_T within $\Delta R = \sqrt{(\Delta\phi^2+\Delta\eta^2)} = 0.2$ of photon candidate must be < 2.6GeV (2.2GeV) for 8TeV (7TeV) data
  - Isolation cut on additional E_T within $\Delta R = \sqrt{(\Delta\phi^2+\Delta\eta^2)} = 0.4$ of photon candidate must be < 6GeV (5GeV) for 8TeV (7TeV) data
  - Only 2-photon events retained
  - Diphoton vertex reconstructed from longitudinal shower profile for un-converted photons, otherwise from conversion tracks, using Neural Net

CMS ttH results

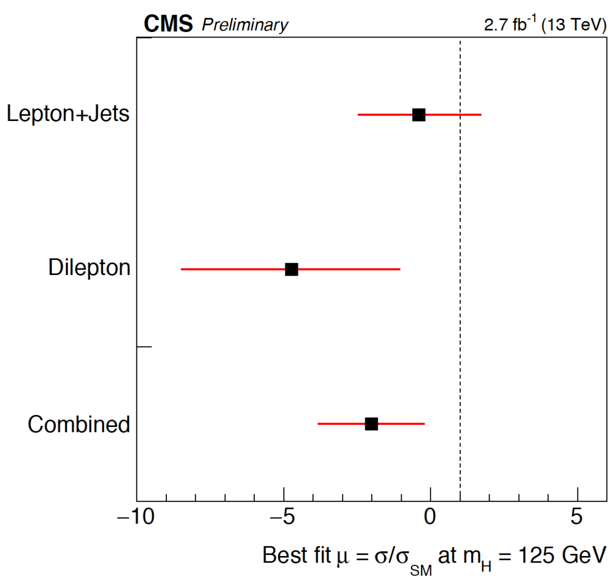
7+8TeV combination: μ = 2.8 ± 1.0



13TeV multilepton



13TeV H->bb



13TeV combination